Master's degree thesis

LOG953 Logistics

Planning and optimization of the petroleum products distribution network

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Number of pages including this page: 94

Molde, May 2022

Molde University College
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Preface

This thesis completes the Master's Degree in Renewable Energy Logistics at the Molde University College, Specialized University in Logistics. Work on this thesis was carried out from mid-December 2021 to the end of May 2022.

First and foremost, I express my sincerest gratitude to my supervisor, Anna Konovalenko, for her support, patience, motivation, enthusiasm, and knowledge that she was sharing with me during the period of working on my thesis. I couldn't imagine a better mentor for my thesis. Under her proper supervision and expert guidance, I was able to successfully write my thesis. She also gave me some useful advice whenever I was in doubt.

I would also like to thank Lars Magnus Hvattum, my co-supervisor, for his wise comments, suggestions, professional advice, and guidance that helped me finish my thesis smoothly.

Furthermore, I want to thank Molde University College for giving me the opportunity to study abroad in Norway during these two years, which made my dreams come true.

Abstract

Oil companies must deliver the right product to their customers (companies and individuals) at the right time, at the best price, and under optimal conditions of safety and environmental protection. This is the purpose of petroleum logistics, which is based on the availability of such facilities as refineries, storage sites, and distribution networks to transport petroleum products to the final consumers. The thesis focuses on the fuel transport optimization network for Gazprom, a state-owned oil and gas company in Russia involved in oil production and the distribution of petroleum products. The purpose is to develop an efficient planning method for a multi-objective petrol station replenishment problem (PSRP) with real characteristics, which concerns the optimization of the distribution of gasoline to the network of gas stations during a given planning horizon. Considering the most relevant real characteristics of the problem leads to designing models that better represent the actual situation of product transportation. Based on Gazprom's task of replenishing stocks at the network of gas stations, a fleet of two types of vehicles of the same capacity was assigned to deliver gasoline from a set of oil depots and determine the most optimal delivery routes with minimal transportation costs. This case study examines a clustering of oil depots and customers with later routing problems involving multiple depots and multiple trips variants of the problem, and vehicle loading with capacity restrictions and availability of split delivery. In addition, one of the operating depots needs reconstruction and must be closed for 2 years. Meanwhile, gas stations located near this depot have to be served by the remaining oil depots and gasoline flows should be redistributed to continue satisfying demand. Thus, the purpose of this study is to contribute to achieving the goals of reducing transportation costs by developing effective planning for the distribution of petroleum products. To find a solution, the problem is formulated as a mixed-integer linear problem. After conducting a preliminary analysis, it was found that the developed mathematical model should be able to deal with planning, transportation, and given constraints. From a business perspective, the model creates a basis for decision-making in a complex and interdependent supply chain, making it possible to reduce transportation costs. The model can be developed for further research by adding time windows, product types, or vehicle capacity variations.

Keywords: vehicle routing problem, petrol station replenishment problem, downstream petroleum supply chain, multi-objective, multi-trip, split delivery, mixed integer linear programming;

Acronyms

VRP - Vehicle Routing Problem

CVRP - Capacitated Vehicle Routing Problem

PSC - Petroleum Supply Chain

SDVRP - Split Delivery Vehicle Routing Problem

MILP - Mixed Integer Linear Programming

PSRP - Petrol Station Replenishment Problem

TSP - Travelling salesman problem

CFRS - Cluster-first-route-second

RFCS - Routed-first-Cluster-Second

CIS - Commonwealth of Independent States

3PL - Third Party Logistics

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1 Introduction

The rapid development of the market, the globalization of business, the increase in the number of facilities included in the supply chain, the fierce competition, and the requirement to improve the quality of consumer service pose more and more new tasks and challenges for oil and gas companies, including, among other things, the fastest and most competent delivery of goods to the end consumer (Chima, 2007). Petroleum logistics is the management of flows that occur at all stages and links of the organizational and technological chain of production and supply of oil products and gas in order to meet fully consumer demand at the lowest operational cost within the conditions of optimizing the activities of enterprises. Petroleum logistics includes many activities such as demand forecast, site selection, material procurement, product-specific packaging, warehouse and inventory management, customer and supplier order process, transport management, shipping, and reverse logistics (Li, 2014).

When addressing the oil and gas industry, we usually distinguish between the following three segments: upstream, midstream, and downstream. The different segments refer to the different stages a resource goes through, from oil production to delivery of petroleum products to the end consumer (Amor and Ghorbel, 2018). In this thesis, the focus is placed on the last segment, namely, downstream logistics in which crude oil is converted into finished products and in turn distributed for commercial or trading purposes. Downstream logistics globally defines all supply chain activities aimed at making finished products available to customers or end users. This is part of the logistics that consists of transporting processed products to the customer (directly to his/her home in the case of delivery to the consumer or to a place where the customer can buy the product). As part of downstream logistics, the service provider responsible for this activity must comply with the scale of the distribution network, the deadlines requested by the clients, capacity constraints, and the delivery volumes. In a highly competitive environment, downstream logistics strives to deliver the product to the final consumer at the best possible cost terms and time. Since downstream transportation accounts for 65 % of global oil consumption (AMCS Group, 2017), there is ample opportunity to optimize this part of the petroleum industry. There are a number of existing models by applying which a company can reduce transportation costs significantly and optimize the sequence and frequency of visits to counterparties. According to Jespersen and Nielsen

(2004) efficient logistics depends on many factors, for example, how well the transport system is structured in terms of accuracy, quality, cost, duration, timeliness, frequency, distance, and time. Therefore, efficient and optimized transport systems are strategically important for the effective distribution and retailing of oil and petroleum products. In this research, development and optimization of petrol station replenishment problems are considered.

Objectives

The main purpose of this Master's thesis is to investigate the downstream logistics problem with a focus on the petrol station replenishment problem and develop a model for planning and optimizing Gazprom's transportation network, namely the distribution of fuel from a set of depots to the network of filling stations with later redistribution of fuel flow when one depot is closed for reconstruction.

In order to fully achieve the main purpose of this Master's thesis, intermediate objectives have to be accomplished:

1) exploring the oil and gas supply chain and especially the downstream segment in detail;

2) building up a literature review on the given topic, studying publications and materials on downstream oil and gas logistics topics as well as optimization related literature;

3) cleaning, grouping, mining and analyzing the necessary data from the Gazprom company;

4) creating a real distance matrix by using Google API;

5) defining and characterizing the problem approached in the model;

6) implementing a Mixed Integer Linear Programming (MILP) model and testing the model with different sets;

7) adding clustering of customers and depots;

8) testing the redistribution of fuel flow among remaining operating oil depots and

filling stations when one depot is out of service;

9) implementing the real data and analyzing the results.

Methodology

Logistics as a science is at the intersection of the possibilities of using qualitative and quantitative methods and taking into account various factors in a model that most adequately reflects the patterns of functioning of the supply chain system.

Recently, there has been significant progress in the use of quantitative methods in the development of logistics systems and the widespread use of computer technology. The list of logistics problems being solved by applying these methods is constantly growing, and examples of successful applications can be found in almost all functional areas. Quantitative methods are used in tasks such as location problems, transportation, and inventory; more detailed, route design for vehicles using simulation models to maximize return on investment; transhipment problems using linear programming; network models when developing a distribution network and choosing a product set.

The most well-known operational analysis procedure is linear programming, a mathematical optimization tool that underlies network management, integer programming, and transport problems. There are many interrelated variables in the logistics system, and this would seem to create the prerequisites for solving problems using linear programming.

The type of this thesis is a quantitative study based on a case task of Gazprom, an oil and petroleum products production and distribution company. A study was carried out to understand the current practice in the oil distribution industry and identify emerging difficulties and challenges in the oil supply chain and specifically in Gazprom. Quantitative studies focus on counting and measuring, and the thesis aims to determine how many vehicles and which routes should be used to serve all customers under vehicle capacity restrictions. To achieve the above-mentioned goals, a model for the Petrol Station Replenishment Problem has been introduced, which is a variant of the Vehicle Routing Problem. The Petrol Station Replenishment Problem is applied by adding a set of multiple depots, allowing multiple trips and splitting deliveries. After the introduction of an accurate model, this optimization approach was extended to obtain optimal routes in the case when one depot is closed for the reconstruction. Potential solutions have been proposed to help the company improve customer satisfaction while reducing costs when redistributing petroleum product flows.

Structure

This thesis consists of eight chapters, structured as follows. The first chapter presents an introduction, objectives to be achieved during the execution of the project, and a methodology to be followed in order to fulfill these objectives. The second chapter includes an overview of the oil and gas supply chain, focusing mainly on the downstream logistics sector. The third chapter is a literature review, which reveals the sources of information and resources used and studies with similar logistical problems for the petrol station replenishment problems and clustering. The fourth chapter contains a detailed description of Gazprom operations in the chosen region, as well as a characterisation of the case study and an explanation of data collection methods. It provides all the information needed for both model creation and optimization. The fifth chapter presents a mathematical model developed for this case. The sixth chapter introduces a solution method, which explains how experiments are carried out to solve the model with clustering and later routing. The seventh chapter is a computational part with a description of the experiments conducted while implementing the model and the following results. The last chapter completes the Master's thesis and includes conclusions and suggestions for further research.

2 Overview of Petroleum Supply Chain

This chapter is intended to provide an overview of the structure of the oil supply chain in general terms and to raise the issue of the importance of applying methods for optimizing operations in the Petroleum Supply Chain (PSC). In addition, the last stage of the supply chain, namely downstream logistics, which is the main topic of this research, is considered in detail. The activities included in this sector of the supply chain are mainly related to the distribution of petroleum products and used optimization models attempt to find the optimal solution to maximize profits or minimize transportation costs by making decisions regarding many activities such as finding the most optimal routes, scheduling the modes of transport used and determining the amount of each product to be transported.

2.1 Petroleum Supply Chain

Nowadays, the transport and logistics industry is becoming an important component of many fields due to the increase in the volume of cargo and product transportation. This is especially noticeable in the oil and gas sector, one of the basic industries of many countries. Today, the oil and gas industry provides more than 50 % of all energy worldwide (British Petroleum, 2021). Other renewable energy sources in use, such as wind and solar energy, have greatly increased their share in recent decades and their consumption nearly doubled between 2000 and 2019 in some countries (Congressional Research Service); however, they are still far from surpassing fossil fuels and their products. Therefore, it is quite clear that the world and manufacturing will continue to depend on the oil and gas industry and petroleum products for several decades to meet their energy needs.

Meanwhile, transportation of products in the oil and gas industry through the whole supply chain is a complex and expensive operation (Kazemi and Szmerekovsky, 2015) as it includes moving the material flow from the starting point (well) to the end consumer (gas stations, retail stores for oils and lubricants, and refineries). The logistics divisions of oil and gas companies are currently solving problems, jointly with construction, drilling and field divisions, by extending and developing their supply chains, sometimes, even in the absence of infrastructure and in difficult climatic conditions which makes it even more challenging. Oil companies and their contractors are always looking for the most efficient strategies and ways to transport their products between oil fields, refineries, supply bases, and final customer locations. However, difficulties connected with a great number of facilities included in the supply chain and huge volumes of products to be delivered prevent this goal from being fully realized (Lima et al., 2021). Such problems include unpredictable failure of one of the links in the supply chain, inaccurate planning and forecasting and unforeseen demand, which must be considered. The logistics system is based on probable patterns of changes in the functioning of network chains (oil bases, fuel stations, refineries) as well as the influence of other internal and external factors on the activities of an oil and gas company (Mirhassani, 2008). Thus, the supply chain must be flexible enough to withstand any shocks, major or minor, that occur in the movement of material flows (Saad et al., 2018).

The main trends in the development of logistics in production include the willingness of companies to fully satisfy customers' demands while reducing transportation time and costs. Today, logistics plays a strategic role in a competitive market since it provides a means to search for new sources to increase the efficiency of enterprises by optimizing the interaction of the constituent elements of the company's resource potential. The most important condition for the further development of the oil and gas industry should be the development of advanced logistics systems in order to increase the level of organization of complex management on the basis of better service support for oil-producing enterprises. The implementation of such enhanced logistics concepts can help to reduce the time losses of the production cycle and delivery time, maintain stocks of materials and control outbound deliveries of finished products, and enhance innovation processes and compliance with contractual obligations while strengthening the integration of all material flows in the production process (Lisitsa et al., 2019).

The petroleum industry is usually divided into upstream, midstream, and downstream activities. The first part covers the exploration, production, and transportation of crude oil and gas up to the point of conversion into final products (mainly refineries) (Manzano, 2005). Later activities are related to the processing of crude oil in the refineries, distribution and marketing of all refined products (Alvarez et al., 2018). In this thesis, the focus is placed on the last stage of the supply chain, paying special attention to the activities of transporting and distributing petroleum products from the tank farm to the gas station, which will be discussed in the next section.

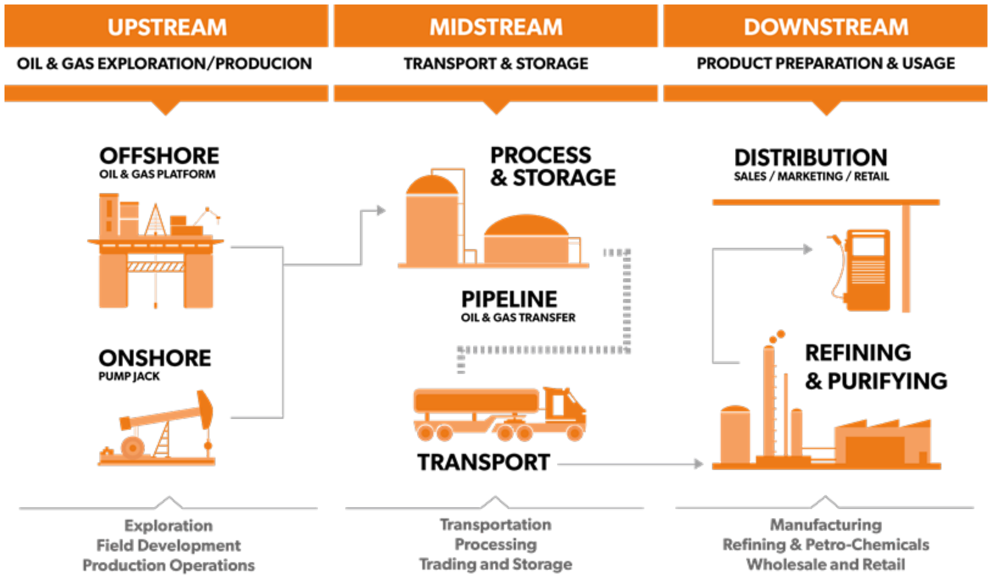

Figure 1: Petroleum supply chain infographic.
(Eland Cables)

2.2 Downstream logistics

As specified by Manzano (2005), the downstream part of the oil and gas industry includes refining, supply and wholesale distribution, and marketing of a large number of materials, semi-finished products, and products. Providing enterprises and customers with fuels and lubricants plays an important role in the country's economy since petroleum products are still one of the world's best-selling commodities as they continue to be the main source of energy for the transportation industry, utilities, and agricultural industry that can not operate without fuel, oils, greases, and solvents (Adenigbo et al., 2017).

One of the biggest challenges is to implement technology strategies in the downstream supply chain to optimize operations and save transportation costs while meeting the demand of real and potential consumers as companies have to consider many factors and restrictions that make the process of transportation complex and challenging, with the need to apply new and diverse techniques and approaches. Such restrictions may include a limited number of available trucks and drivers, regulatory policies and difficulties associated with inherent product characteristics (mostly flammable liquids that need to be transported in specialized multi-chamber trucks and trailers), heterogeneity of customer demand and tight time frames. So, a number of requirements and recommendations are put forward for the transportation of fuels, which each carrier is obliged to comply with, otherwise, the transported product will lose its original quality indicators, delivery will not be performed on time, or not all customers will be served. The requirements relate to both the transportation technique and the conditions that can help to avoid emergency situations. In addition, logistics is strongly influenced by the geographical location of network facilities, as well as the availability of accessible railways and roads, and oil product pipelines.

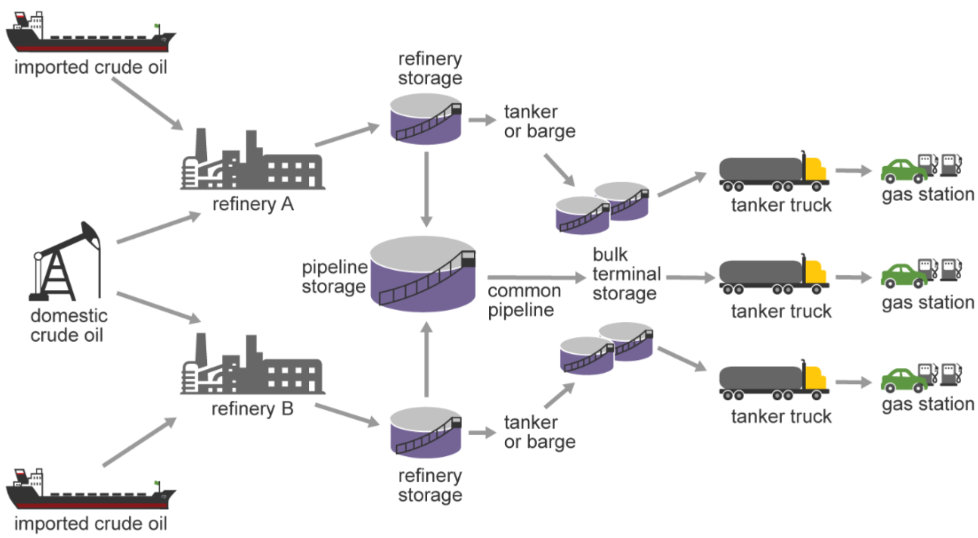

Figure 2: Flow of petroleum products.
(Energy Information Administration, 2017)

The main criteria for successful optimization on the strategic horizon are the reduction of logistics costs, which above the other expenses include transportation costs for primary logistics (tariffs for the delivery of oil products by pipelines and rail transport) and secondary logistics (tariffs for delivery by road to the final consumer: a gas station or a small wholesale buyer).

Accordingly, solving the problem of optimal network development may require generating and testing a large number of hypotheses and questions such as:

1) What new facilities (oil depots, filling stations) need to be opened, leased, or shared with other companies?

2) What facilities should be abandoned (closed, mothballed, leased out)?

3) For what objects, in what volume and when is it necessary to carry out current maintenance repairs, and for which - to carry out modernization and expand throughput characteristics? For how long will the facility be closed?

4) What modes of transport do companies need to use to operate in the region? Should they use the 3PL fleet of vehicles?

5) What are the requirements for the network of gas stations and for the search for small wholesale customers to achieve competitive advantages when working in the region?

Despite the many already existing improvements in the processes and technologies of the logistics system implemented over recent years, there are still problems with supply chain transportation costs and process inflexibility (Fernandes et al., 2013). Any solution in this area will need to integrate more complex models and use advanced technologies. The downstream supply chain challenges are actually opportunities for innovation and new models to get the system to work most efficiently.

To sum up, logistics in the oil and gas industry, and especially in the downstream part faces many challenges and a number of problems. The topic of this thesis is especially relevant due to the fact that the conditions and requirements for the transportation of petroleum products are becoming more stringent and complicated, therefore, the demand for high-quality logistics services is growing and there is a need for integrated logistics solutions for supply chain management in the oil and gas industry. However, it is possible to reduce various transportation costs and properly monitor the movement of petroleum products with the aid of an advanced supply chain and optimization approaches.

3 Literature Review

The purpose of this chapter is to review the literature describing methods and approaches for optimizing oil and gas logistics in general and downstream logistics in particular. Various sources have been used while writing this Master's thesis. The themes, which are followed in this research, are "Downstream Logistics", "Petrol Station Replenishment Problem" and "Modeling and routing optimization"; so, information about the theoretical aspects of logistics as well as the principles of the oil and gas supply chain were studied. Most of the articles were taken from platforms such as Science Direct and ResearchGate. More than 50 articles were found as a result of the search, but only the most relevant and actual ones to the topic of downstream logistics were analyzed and described in this chapter.

As the purpose of this thesis is to create an optimization model that is applicable to create a route plan and the schedule for the delivery of oil products, references to research with existing optimization models are made. Investigation of these models and used methods was done in order to improve them and obtain better results for this case study.

3.1 Petrol station replenishment problem

In order to ensure a stable supply of petroleum products to meet growing demand, many suppliers are faced with an extremely complex process of planning strategies for distributing these products to their customers, which include gasoline retailers (gas stations) and manufacturing companies. This process generally requires the allocation of several competing resources while simultaneously complying with many operational constraints and regulatory policies. On the example presented in this thesis, which refers to the distribution of fuel from the tank farm to gas stations, this transportation problem is analyzed. The gasoline distribution problem is known in the literature as the Petrol Station Replenishment Problem, which deals with the distribution of petroleum products from a warehouse to a number of gas stations using a fleet of vehicles, and the goal of which is to find the most optimal set of routes according to the objective function and without violating operating constraints. As the vehicle fleet increases, transportation costs need to be reduced, companies are resorting to efficient planning and optimization techniques. The PSRP is a variant of a vehicle routing problem with complicating and constraining features to represent the complexity of a real-life situation. These complications may include a heterogeneous fleet of vehicles, an extended time horizon, an oil depot with unlimited inventory, multiple stops per trip, split loads, and time windows.

The PSRP task can be optimized at different levels of planning within the company. In a paper presented by Lima et al. (2016), a distinction is made between the strategic, tactical, and operational levels. Strategic planning is concerned with decisions with long-term implications that determine the structure of the supply chain, which inhibits tactical planning, where medium-term decisions are about determining the best flow of materials along the chain, in addition to setting an operational level that copes with short-term decisions related to scheduling activities. This thesis focuses on the operational level as a fixed network is considered for short-term planning.

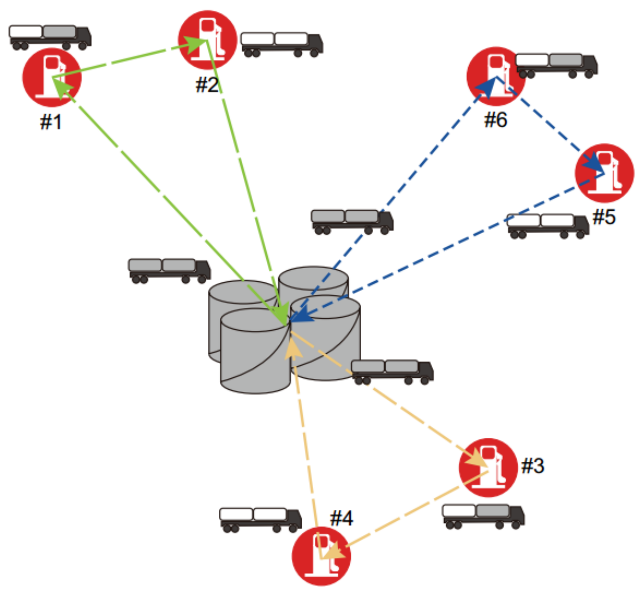

Figure 3: Flow of petroleum products from oil depots to the gas stations.
(Wang et al., 2019)

In recent years, a large number of studies have been carried out to optimize the planning and management of the distribution of oil and petroleum products and have shown that routing planning methods provide significant cost savings of up to 25 % according to Avella et al. (2004).

Sear (1993) was one of the first to study strategic supply chain planning in the downstream industry and outlined its importance. He described the types of transportation used and the main classes of products transported within the downstream sector, as well as the business risks associated with changing the logistics infrastructure. His paper outlined business decisions that need to be addressed for crude oil purchasing processes, transportation to the oil depots and customers. Considering different costs at each stage of the supply chain, he developed the linear optimization model for the minimization of the cost of delivering oil products to the end customers. Brown and Graves (1981) were also among the first to study the problem of supplying gas stations with the aim of minimizing transportation costs while maintaining a fair distribution of the workload of people and equipment, safety and customer service standards, and compliance with equipment compatibility restrictions. They studied a highly automated, real-time dispatch system that uses built-in optimization routines to replace extensive manual operations and significantly reduce operating costs for a fleet of more than 300 oil tanker trucks making approximately 2,600 loads per day from 80 depots.

Cornillier et al. (2008a) also began to study the problem of supplying gasoline to a network of gas stations, breaking it down into a truck loading problem and a routing problem, based on a real case that arose in Quebec East. In the study of Cornillier et al. (2008a), an unlimited heterogeneous fleet of tank trucks with the same compartments was considered in order to determine delivery volumes in a given planning interval, distribute specific products to tank truck compartments, and develop delivery routes to gas stations from the main depot with a limitation on the number of stops per trip to make it possible to find the optimal solution. The transportation cost was calculated as a condition proportional to the mileage and a fixed part depending on the usage of vehicles. The routing problem has been addressed using two strategies based on the mapping approach and on the column generation scheme. Then, they continued to study the PSRP problem with the help of heuristics, and in the next article, Cornillier et al. (2008b) consider a multi-period problem of replenishment of gas stations in order to optimize the delivery of various petroleum products to a set of gas stations on a given planning horizon. In the course of solving the problem, it was determined how much of each product should be delivered to each customer, how to load these products into the compartments of vehicles, and how to plan the routes of vehicles in order to maximize the overall profit. Subsequently, they updated their research by expanding the problem to a multi-depot variant with time windows for customer visits, where each depot has its own fleet of heterogeneous tankers (Cornillier et al., 2012). The authors developed a heuristic that requires generating trips rather than routes, as in previous studies, so trips are generated differently. They proposed a mathematical model that selects from a set of allowed trips a subset that satisfies all needs, maximizing the total daily net income. They used a two-phase procedure in which they first built an initial trip set and then chose a subset of that set to get the required set, which gives a good but not necessarily an optimal solution.

Fernandes et al. (2013) presented a MILP model for the design, modernization, and planning of downstream oil supply chains, based on a real-life Portuguese case that includes petroleum product production at local refineries and supply from a regional center. In their paper, Fernandes et al. (2013) discussed a multi-echelon, multi-product, and multi-transport downstream network with resource capacities, supply sources, and demand requirements. A Deterministic Mixed Integer Linear Program is created for the strategic design and planning of the downstream network, which determines optimal depot locations, capacities, modes of transport, optimal routes, and network impact for long-term planning. The MILP maximizes the multi-echelon total profits of oil companies in the supply, refining, distribution, and retail phases. The authors later expanded their research with a dynamic MILP, which introduced collaborative design and tactical planning with multi-stage inventory while maximizing profits (Fernandes et al., 2014).

Vidovic et al. (2014) considered solving the inventory routing problem of filling stations with a homogeneous fleet of vehicles with compartments for fuel distribution and presented MILP and heuristic models that minimize inventory and routing costs and account for costs per fleet and limit each route by the number of customers visited to observe the impact of these costs on the resulting solutions. Unlike others, Benantar et al. (2014) considered the Inventory Routing Problem with multiple compartments with time windows without limiting the number of customers served along the route. For this problem, an efficient tabu search algorithm was used, which was tested on a set of vehicle routing problems with a time window, as well as other realistic instances. The results are compared with MILP, with heuristics described in the literature, as well as with results extracted from company business plans.

3.2 Vehicle Routing Problems and extensions to the basic CVRP

Currently, companies are trying to manage their resources efficiently and come up with profitable strategies to improve their services, find the most optimal routes for the vehicles, and fully satisfy customers (Saad et al., 2018). Significant cost of functioning and developing the distribution network, as well as maintaining facilities, forces companies to actively solve the problem of cost optimization. Hence, it is important to focus on the logistics sector, which is considered to be a key factor in the competitiveness of a business, especially in the delivery of goods (Tlili et al., 2016). The routing phase is considered to be a fundamental logistical cost issue. Analysis of the most convenient routes that a vehicle should take can be achieved with vehicle routing problems approaches according to Ghannadpour and Zarrabi (2019). In this regard, interested researchers have addressed various variants of routing problems and optimization tools for them. Local transportation is usually considered as the most expensive component in the distribution network of logistics systems (Mirhassani, 2008). In many areas of the market, the delivery of a product adds to its value an amount comparable to the cost of the product itself. Fortunately, the development of optimization methods for delivery and transportation can often be expressed in savings of the order of 3-20 % of its total cost (Chandra and Fisher, 1994). As a result, the problem of solving transport routing problems is becoming more and more relevant and in demand, the main goal of which is to create optimal routes for vehicles that serve a given number of customers.

When organizing the transportation of goods and cargo in logistics, various methods, approaches, and models for choosing routes are used, the combination of which depends on the conditions for the delivery of products, the parameters of the external environment in which transport vehicles operate in logistics systems, as well as other factors. A class of such problems is called vehicle routing problems and they usually arise during the transportation of goods by commercial or public transport. Collection of household waste, gasoline delivery, snowplow, and delivery of mail are the most famous examples of the VRP (Liong et al., 2008).

The objective of a basic VRP is to minimize the costs associated with serving customers (meeting demand) or travelling distance when the beginning and end of all vehicle routes are located in the depot, and each customer is visited exactly once. The total demand of all customers on the route must be less than or equal to the capacity of the vehicle.

Dantzig and Ramser (1959) were the first to present the "Truck Dispatching Problem" with research and investigation of how a fleet of homogeneous trucks can serve the gasoline demand of a network of gas stations from a central bulk terminal with the objective of finding a way to assign stations to trucks in such a way that station demands are satisfied and total mileage covered by the fleet is a minimum. A couple of years later, Clarke and Wright (1964) extended this problem to a typical linear optimization problem commonly used in logistics and transportation fields that enables the rapid selection of optimum or near-optimum routes. Namely, how to optimally serve a group of customers geographically dispersed around a central depot using a fleet of trucks of various capacities.

It should be taken into account that modern VRP models are very different from the models introduced about 60 years ago by Clarke and Wright (1964) and Dantzig and Ramser (1959) who mainly took into account the capacity of the vehicles. New generation models are aimed at considering and taking into account real constraints and problems, such as time windows for warehouses or delivery times to a customer, a combination of different modes of delivery, constantly changing demand and supply, and changes in delivery times due to traffic jams. These features introduce significant complexity to the vehicle routing problem. The Class of VRP is a well-known integer programming problem that belongs to the class of NP-hard problems, which means that the computational complexity of the problem depends exponentially on the size of the input data (Baldacci et al., 2011). So, the task is also complicated by its scale, as the models can include thousands of customers and hundreds of depots, from which delivery will be carried out by various modes of transport, taking into account any restrictions. More variants and extensions to the VPR problem can be found in Golden et al. (2008).

To sum up, the purpose of the VRP is to determine the routes to be used and create a schedule for vehicles in order to satisfy customers' demand and minimize transaction costs. In addition, the duration of the trip, its length, costs, or the number of vehicles used can be minimized as well. Moreover, the conditions for many constraints must be met, such as restrictions on the capacity of the vehicle, route duration, time windows, number of nodes to be visited, duration of drivers' work shifts (Palmgren, 2005). There are a wide variety of variants of the routing problem. Basically, in most options, the task parameters are deterministic, so planning delivery routes is simplified even if a large service network is considered. But still, interest in VRP arises due to its practical significance with considerable complexity.

Several variations and specializations of the vehicle routing problem exist based on the type of the transported goods, the required quality of service, and the characteristics of the customers, depots, and the vehicles. This thesis takes into account several aspects of VRP. First, the optimal route for visiting the gas station in order to deliver gasoline for each of the vehicles must be found. Secondly, the number of routes and the sequence of customer visits within each route must be found for each vehicle. Thus, in this particular thesis, a combination of different variants at the same time are applied, namely: Capacitated Vehicle Routing Problem (CVRP), Vehicle Routing Problem with Multiple Trips (VRPMT), Split delivery Vehicle routing problem (SDVRP) and Multi-Depot Vehicle Routing Problem (MDVRP).

1. **Capacity Vehicle Routing Problem (CVRP)**

   The CVRP is considered to be the most common and studied among others because it is used in the transportation of food, fuel, and retail goods (Iswari and A., 2018). The CVRP has the objective of finding a set of routes with minimum transportation costs when the fleet of homogeneous vehicles initially located at the several depots serves the deterministic needs of a group of customers while respecting carrying vehicle capacity limits (Borcinova, 2017). Baldacci et al. (2007) present in the paper an overview of the most recent developments that have had a major impact on the existing algorithms for solving CVRP as well as reports on a comparison of their computational performance. In addition, a variety of heuristic methods and algorithms for the CVRP appears in (Breedam, 2001) and (Toth and Vigo, 2002).

2. **Multi-Depot Vehicle Routing Problem (MDVRP)**

The MDVRP is a generalisation of the VRP, where vehicles depart from and return to one of the multiple depot locations with the objective to find the least cost vehicle routes to satisfy the demand of a set of customers. Therefore, besides the definition of the vehicles' routes, it is also necessary to decide from which depot the customers are visited. For the Multi-Depot Vehicle Routing Problem, there are still not many algorithms and methods available in the literature compared with the extensive literature on VRPs and their variants, while several heuristic procedures have already been proposed. Regarding exact algorithms, Laporte et al. (1988) have developed branch and bound tree algorithms for solving the asymmetric version of the multi-depot vehicle routing problem by using an appropriate graph representation, and then a graph extension. Later, Lim and Wang (2005) proposed two solution methodologies for the multi-depot vehicle routing problem with fixed vehicles distribution (MDVRPFD). The first iteration assigns customers to depots, then the TSP algorithm is followed to solve the sequencing problem for each depot. In the second iteration, assignment and routing tasks are solved at the same time since clients are distributed to depots when routes are established.

3. **Split Delivery Vehicle routing problem (SDVRP)**

The SDVRP considers a fleet of homogeneous vehicles with the same capacity to serve a group of customers, and each customer may be visited more than once, contrary to what is usually assumed in the classical Vehicle Routing Problem, and each customer's demand may exceed the vehicle's capacity (Archetti and Speranza, 2008). In the SDVRP, each vehicle must start and end its route at the same depot. The problem is to find a set of vehicle routes serving all customers so that the sum of the delivered quantities for each trip does not exceed the vehicle capacity and the total distance while keeping travel distance to a minimum. One of the first contributions to the study of SDVRP was published approximately 30 years ago by Dror and Trudeau (1989), who considered SDVRP as a delivery cost-reducing approach by allowing separate shipments by any number of vehicles. Significant cost savings are achieved both in terms of total distance and the number of vehicles required. Archetti et al. (2006) analyzed the maximum possible savings obtained by splitting supplies and showed that the savings in delivery costs that can be obtained by allowing split deliveries are at most 50 %. A few years later, Archetti et al. (2008) presented the benefits of allowing split deliveries in their new research and determined the practical implications of split deliveries for different customer characteristics in terms of geographic and demand distribution. The benefits are the following: reducing the number of routes and, correspondingly, vehicles as well as the delivery costs.

4. **Vehicle Routing Problem with Multiple Trips (VRPMT)**

   The VRPMT is a variant of the classic VRP, in which it is considered that each vehicle can make several trips to fully satisfy customers' demands. One of the first studies in the literature to include the idea of a multiple trips variant for VRP was presented by Taillard et al. (1996), in which the same vehicle can be assigned to multiple routes within a given planning period. A tabu search heuristic has been developed for this problem, and it has been shown that it gives high-quality solutions for a number of test problems. A few years later, Brandao and Mercer (1997) published a paper about VRPMT based on the case of Burton's Biscuit Ltd company. This research took into account the actual requirements and conditions of Burton's Biscuit Company, allowing multiple trips of vehicles with different capacities. In addition, the time windows problem was included, as well as restrictions regarding the working hours of drivers and the time of loading and unloading vehicles. Moreover, it was possible to rent additional vehicles if the company's own car fleet was not enough to satisfy demand. As a result of the research, it was concluded that the multiple trips approach was the most effective option for this company and allowed them to reduce transportation costs. Additionally, the work of Petch and Salhi (2004) proved that by allowing multiple trips, companies can achieve savings on transport costs and also noted that VRPMT can be important for both tactical and strategic planning of a company's supply chain. Their solution approach consists of a multi-stage construction heuristic, which can be seen as a combination of the two solution approaches mentioned in Brandao and Mercer (1997) and Taillard et al. (1996).

5. **Multi-Objective Vehicle Routing Problem (MOVRP)**

Vehicle Routing Problems are usually used for the simulation of real data-based cases. However, in order to simplify these problems, they are often considered with the single-objective of minimizing the total cost or distance, despite the fact that most of the problems that arise in industry, especially in logistics, are multi-objective (Jozefowiez et al., 2008). Variant Multi-objective Vehicle Routing Problem (MOVRP) has several objective functions, taking into account inequality and equality constraints for optimization(Deb, 2001) with a goal is to find a set of solutions that satisfy all given constraints. For instance, Bowerman et al. (2008) proposed school bus route planning that would ensure an equitable distribution of services among all students located in different city areas. The goals were: minimizing the total route length, minimizing the total walking distance of students, and maximize the loading of buses. Another example is the paper by Gupta et al. (2010) in which they presented a study with the overall goal of developing bus service for a Jain University of Bangalore plan to pick up and drop students and staff from/to home and university. This study considered such objectives as maximizing customer satisfaction, minimizing the size of the fleet, minimizing the distance, and minimizing the waiting time with capacity limitation.

Many algorithms for tackling multi-objective problems have been proposed in recent years. These strategies can be divided into three general categories: (1) scalar methods, (2) Pareto methods, and (3) methods that belong to neither the first nor the second category (Nahum et al., 2014). Some algorithms for solving multi-objective problems are based on decomposition, which splits a multi-objective problem into a set of single-objective problems which are alternately connected to the model. In this thesis multi-objective problem expressed as summation of two objective functions with the same weight.

3.3 Clustering

To solve the VRP problem concerned in the thesis, clustering was applied before developing route plans. Clustering is the division of a set of input nodes into groups (clusters) according to the degree of "similarity" to each other according to Lucińska and Wierzchoń (2012). A logistics cluster is a stable interaction of independent geographically concentrated locations that implement logistics functions, whose efforts are aimed at maintaining a full cycle of main and associated flows and end-to-end optimization of resources from initial suppliers to end consumers as well as the development of transport infrastructure and the improvement of transport services. Clustering gains value when it acts as one of the stages of data analysis, building a complete analytical solution. It is often easier to identify groups of similar objects, study their features and build a separate model for each group than to create one general model for all data. In order to compare objects, it is necessary to have a criterion based on which the comparison will take place. In this case, such a criterion is the distance between objects.

Several clustering approaches have been suggested and applied, with the majority of them finding superior or optimum clustering results. Clustering in optimization can be performed by different approaches, meanwhile, various variants of heuristics are the most applicable methods for splitting customers into clusters. When considering the multi-depot problems, cluster-first-route-second (CFRS) is commonly used. This approach for solving CVRP is usually applied as two-phase heuristics and is used to minimize the total length travelled by vehicles since the original problem is split into smaller subproblems by grouping clients into clusters. The idea of this solution according to Beasley (1983), who was among the first to propose proposed the CFRS and Routed First-Cluster Second (RFCS) strategies, involves two stages of decisions (1) assigning customers to clusters depending on distance first and (2) sequencing the delivery in each cluster to get the assignment and routes of the vehicle. Thus, the main idea is to assign clients to a particular depot from which they are served (Shalaby et al., 2021). Another example is a hybrid heuristic (Mirabi et al., 2010) which was used for assigning customers to depots, finding the delivery routes and selecting the vehicle fleet composition.

Past studies that have applied clustering in solving CVRP have generally used the k-means clustering method where each customer belongs to the cluster with the nearest mean, and the resulting centroids are derived from geographic locations (Mostafa and Eltawil (2017), Singanamala et al. (2018)). In addition, capacity of depots also can be considered in clustering. For instance, Le et al. (2022) assigned clients to clusters with k-means clustering approach in respect that total demand of customers could not exceed the capacity of depots.

4 Case study

The purpose of this chapter is to present, describe, and characterize a real case study given by Gazprom considering downstream logistics that was applied to the developed optimization model. Namely, the problem of distributing gasoline from a set of oil depots to a network of gas stations in one of the regions of Russia in order to fully meet customer demand along the most optimal routes, which can help to reduce transportation costs. In addition, the problem considers the redistribution of gasoline flows between depots and filling stations in the event that one depot goes out of service due to reconstruction.

4.1 Gazprom Neft

Gazprom Neft PJSC is a Russian vertically integrated oil company, one of the Russian leaders in terms of oil production, refining, and efficiency. Its main activities are exploration and development of oil and gas fields, oil refining and sale of petroleum products (Gazprom, b).

The Gazprom Neft Group includes more than 80 oil-producing, refining, and marketing enterprises in Russia and operates in the largest oil and gas regions: the Khanty-Mansiysk and Yamalo-Nenets Autonomous Districts, Tomsk, Omsk, and Orenburg regions (Gazprom, c). The main processing facilities of the company are located in the Omsk, Moscow, and Yaroslavl regions, as well as in Serbia. In addition, the company is implementing mining projects outside of Russia - in Iraq, Venezuela, and other countries.

When selling oil and petroleum products, Gazprom's priority is efficient logistics and maximum utilization of its own transport infrastructure in order to reduce delivery costs and optimize transport schemes. Gazprom Neft's products are sold both in Russia and abroad through the developed network of its own marketing enterprises and subsidiaries, which are marketing enterprises that carry out both wholesale sales of petroleum products and retail sales at filling stations. Significant volumes of consumed resources, the range of petroleum products, and the branching and length of transport communications predetermine the relevance of the tasks of improving the oil product supply system, monitoring the process of product distribution, and the quality of transportation planning, as well as the financial resources necessary for them, procurement and warehousing management.

4.2 Real Case Study

Gazprom's fuel is delivered daily to several thousand customers in Russia, including the hard-to-reach territories of the Far North and abroad - these are large wholesale consumers and fuel storage bases, Gazprom gas station networks, and the company's partners. In conditions of the extreme heterogeneity of the quality of transport services in individual regions of the Russian Federation, with an excessively high regional concentration of oil refining capacities and the widespread consumption of different types of oil products, there is a close dependence on the reliability of oil supply on logistics. An efficient and well-thought-out logistics system is required to effectively serve the growing number of wholesale customers and filling stations throughout Russia. Gazprom owns an extensive network of warehouses and oil depots to store all types of petroleum products in 44 regions of Russia, which significantly reduces delivery times and ensures convenient shipments of branded products for customers from all over the country. The main customer to whom the delivery of petroleum products is carried out is a large network of Gazprom gas stations - a retail network for the sale of petroleum products. The development of its own retail network of filling stations is one of the key areas of the company's work, and at the end of 2018, the Gazprom retail network included 1,809 filling stations (owned, leased, and franchised) in Russia, the Commonwealth of Independent States and Europe, 1,209 of which operate in 36 regions of Russia (Gazprom, a).

The network of tank farms and gas stations located on the territory of the Russian Federation is huge. Therefore, in order to simplify the problem, only the Sverdlovsk region is considered, which is located in the central part of Russia (see Figure 4). There are 6 operating oil depots and approximately 70 filling stations in this region, to which it is necessary to deliver oil products by fuel trucks.

Figure 4: Sverdlovsk region on the map of Russia
(Wikipedia)

This case considers a network of 6 oil depots where gasoline is stored, which must be delivered within a given planning horizon to a number of customers in a gas station network, which is geographically dispersed at a distance radius, allowing to meet demand through daily supplies with the help of splitting customers and depots into clusters according to the distances between them.

4.3 Problem's characteristics

To test the model, a database was created using the example of Gazprom's gasoline distribution network. The data contains the coordinates of the location of the gas station, as well as the depots. In addition, data was issued on the demand for each gas station, transportation tariffs, as well as the time of draining and filling the vehicle. This section presents the data that was received from the company.

Distances: The actual road distances between a set of depots and the gas station network in the considered region were found with the help of Google Maps and the Google API using the coordinates of all the nodes.

Clients: The customers' nodes in the model are a network of gas stations, and all customers have a known demand for petroleum products that must be satisfied. In addition, each customer may be visited more than once, as the demand of some customers exceeds the capacity of the vehicles. Gas stations operate around the clock, so there is no time frame for delivering fuel to customers, which makes the delivery problem more flexible.

Depots: This problem takes into account the presence of 6 depots, which receive oil products from the refinery and then they are delivered to customers. In addition, a certain number of vehicles are attached to each depot, which must start and then finish their route there.

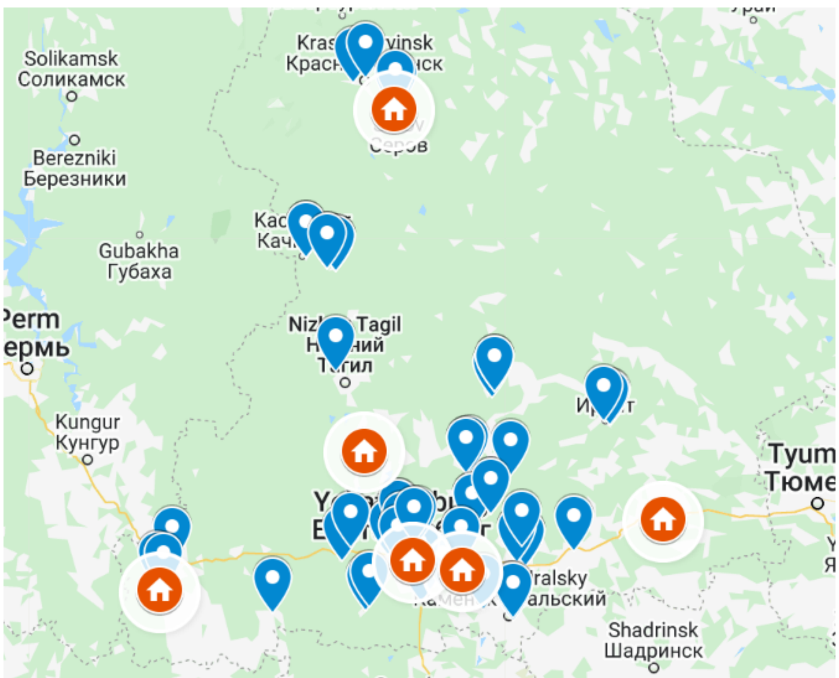

Figure 5: Network of gas stations and depots located in the Sverdlovsk region.

Vehicles: Transportation of petroleum products from the refineries to the end consumer can be carried out by various modes of transport. Due to the fact that gasoline is the most transported petroleum product in the world, it needs to be delivered to the most remote places on our planet, therefore, all existing modes of transport are used for its transportation - rail, road, water, and air (Mirhassani, 2008). The main attention in this case is paid to vehicles delivering gasoline on the road from the depot to customers. There are two types of vehicles used in the model, the own Gazprom's fleet and 3PL vehicles with the same capacity equal to 22.4 tons of fuel. However, each tanker can be filled with no more than 95 % of its capacity, which makes the maximum capacity equal to 21.4 tons. In addition, the model takes into account to which exact depots own and the third-party vehicles are assigned. Namely, how many vehicles of each type are available to deliver gasoline to customers from each particular depot. Each depot has 2 to 3 vehicles of Gazprom's own fleet and 1 to 2 vehicles of a third-party logistics company. The exact data on the number of vehicles can be found in Table 2.

Cost: The cost of using different types of vehicles affects the model and consists of two parts: one part is a fixed cost and the other part is a variable cost. In particular, the use of each third-party fleet vehicle costs the company 500 units on every trip, while the use of its own fleet vehicles is free of charge. The variable cost depends on the distance in km traveled by the vehicle - the delivery area, as well as on the number of tons of fuel that it transports from the depot to the customers. There are 4 delivery zones, and depending on the zone, the travel costs for delivery vary - the farther delivery of gasoline, the cheaper the cost per ton of gasoline per km. The variable cost for using own fleet of vehicles is simplified and does not depend on delivery zones and it is equivalent at all distances to 3.5 units per ton of gasoline per km. All tariffs used in the model to calculate travel cost can be found in the Table 1.

Variable costs, units	
Distance in km	Cost for each tonne of fuel
3PL vehicles	
< 50 51 - 150 151 - 300 > 300	6 5.7 5.5 4.8
Gazprom's vehicles	
any distance	3.5
Fixed costs, units	
Gazprom's vehicles 3PL vehicles	0 500

Table 1: Travel cost.

Delivery time validation: Time frames are not an important issue in this particular case, since gas stations and depots operate around the clock, and customers do not set strict requirements for delivery times. However, in order to ensure that the delivery is completed within the planning horizon (10 days), a limit is set on the total delivery time equal to the number of hours in 10 days - 240 hours. The total delivery time is calculated as the sum of the time spent on filling gasoline into the fuel truck at the depot when refueling (1 hour), unloading gasoline from the fuel truck at the gas station (1 hour), as well as the delivery time from node to node, which is calculated as the travel distance divided by the average speed of the fuel truck, equal to 60 kmh.

Clustering: The problem also needs clustering as a method of dividing it into sub-problems in order to be able to implement large scale data, simplify the case, and obtain more optimal results.

Transportation of oil products from refineries to the filling stations in this case is carried out in two stages:

The first stage: by rail from the refinery to the oil depots.

There is a railway station next to each oil depot since gasoline and other oil products come from the refinery located in Omsk to the Sverdlovsk region on rails in cisterns. At the same time, tank farms can receive from 16 to 20 rail freight transport with gasoline and diesel fuel, depending on the transshipment capacity of a particular oil base. Given that the monthly transshipment capacity of each depot greatly exceeds the amount of gasoline delivered to customers, as well as the fact that the oil depot always has an additional large stock of gasoline, the restriction on the amount of gasoline available for export from the oil depot is not applied either in the model or in clustering because it does not affect the result. Oil depots, to which oil products are delivered by rail, are connected to the main railroad tracks by an access line. At the tank farm itself, the storage of petroleum products in containers and a loading and unloading rack are arranged. The oil depots located in the Sverdlovsk region are designed for the simultaneous storage of different types of fuel, including motor gasoline grades 92, 95, 100 and diesel fuel. Fuel from different cisterns is discharged into single tanks according to the octane number. In this thesis, to simplify the problem, there is no division into types of petroleum products and only gasoline is considered. Transshipment tank farms are used for reloading oil products from one type of transport to another. These are intermediate links between the areas of production and areas of consumption of oil and oil products. Transshipment oil depots, as a rule, are adapted to store a large volume of liquids and can transship oil products both to supply adjacent regions and to other regions of the country. They are very often located near major transportation hubs, such as ports or railway stations. They take part in the turnover of relatively large volumes of petroleum products, as well as in the release of small batches to distribution tank farms. A feature of transshipment tank farms is the minimum shelf life of petroleum products (usually 6-24 days). After draining, some part of the oil product remains stored in the tank farm, but the main part is immediately released into fuel trucks automatically.

The first stage of delivery of oil products is not included into the model and the cost of delivering oil products by rails is not taken into account when implementing a model.

The second stage: by road to the network of filling stations.

All depots have up to 4 available vehicles that supply the filling stations with fuel. The daily delivery process is carried out according to the following steps: the proven and analyzed fuel is loaded onto the determined fuel track and then it is transported to the customer's locations according to the route. The amount of fuel in each fuel truck should not exceed its capacity and all vehicles are equipped with flow meters so that the contents of the tank can be divided into several visiting stations. Each truck can complete more than one trip and visit more than one gas station in one trip. At every location, quantities equal to customer demand (or less) are unloaded from the vehicle, and then the vehicles are moved to subsequent customer locations, where the process is repeated and the truck returned to the depot when the truck tank is empty. More precisely, the trip of the vehicle itinerary describes the sequence in which the vehicle must visit its customers, the amount of product it must load when the vehicle revisits the supply depot and restocks, and the amount of fuel it must deliver during each period when making customer visits. The presence of routes serving one to three filling stations is common in practice. However, there are also situations where oil distribution serves filling stations with a lower level of demand, so in this case, trucks can visit four or five stations within the route. In each delivery trip, all gasoline in the compartment is unloaded, and thus only empty vehicles will be returned to the depot.

Customer orders for gasoline are received in advance, and at the time of route planning, the demand for all gas stations is known. The gas station orders a certain volume of oil products and does not impose special requirements on the delivery time. It is only required that the products be delivered and demand be satisfied within a planning horizon for one or more visits to customers by vehicle.

Gazprom's problem becomes more difficult from a practical point of view, since not the entire fleet of fuel trucks is wholly owned by the company, but some of the vehicles are owned by third-party logistics companies due to the fact that the number of fuel trucks in Gazprom's own fleet is not enough to satisfy fully all customers' demands. Thus, the delivery of petroleum products to the final gas station can be carried out in several ways. In this case, the first option is the delivery of gasoline by the company's own fleet of gasoline tankers. The second option is to additionally use delivery services provided by third-party transport companies operating in the chosen region, which will allow more deliveries. Although the rental of vehicles may be more expensive per unit of distance travelled, there are no maintenance costs. In this case, additional delivery costs must be included in the model, and depending on the type of the truck, whether it is Gazprom's fleet or the Third Party

Logistics (3PL) fleet, travel costs will be calculated differently. When using Gazprom's fleet of vehicles, travel costs are calculated by considering the fixed cost per kilometre for each tonne of fuel. Meanwhile, there is a difference in travel costs for 3PL vehicles depending on the total travel distance and travel zones. In addition, a fixed cost for the usage of 3PL will be added.

An overview of the case study characteristics is shown in Table 2.

Parameter	Value
Number of depots	6
Number of filling stations	66
Number of products	1 (gasoline)
Vehicle capacity	21.4
Number of all vehicles assigned to all depots	24
Number of vehicles assigned to the 1st depot, own fleet and 3PL vehicles	2 and 2
Number of vehicles assigned to the 2nd depot, own fleet and 3PL vehicles	2 and 2
Number of vehicles assigned to the 3rd depot, own fleet and 3PL vehicles	3 and 1
Number of vehicles assigned to the 4th depot, own fleet and 3PL vehicles	2 and 2
Number of vehicles assigned to the 5th depot, own fleet and 3PL vehicles	3 and 1
Number of vehicles assigned to the 6th depot, own fleet and 3PL vehicles	3 and 1
Planning horizon	10 days

Table 2: Case characteristics.

Oil depots have been modernized many times, and technical re-equipment of the 4th oil depot will take place in the near future. Therefore, in case of stopping the operation of a tank farm for modernization, a model is needed that can optimally redistribute the flows of oil products to other remaining operating tank farms in this region with minimal transportation costs. Moreover, in the event that a depot closes, vehicles that were allocated to that depot will continue to operate at other depots.

The efficient logistics of petroleum products supply is aimed at the optimal organization of supplying the population, enterprises and institutions with petroleum products with their rational use and minimal logistics costs. Thus, the creation of the transportation model will make it possible to reduce the cost of transporting petroleum products and make the entire supply chain more transparent. And most importantly, it allows a company to supply filling stations with fuel of guaranteed high quality on time.

In addition, this work is a special contribution to downstream logistics as it is based on a real case of planning the distribution of fuel to oil depots by a leading Russian oil and gas company Gazprom. Due to a large number of demand points, the company's difficulties lie in the fact that at the moment there is no effectively working model of a network that can be adjusted or changed according to the new conditions for the delivery of petroleum products from oil depots to gas stations. In this connection, it is possible to distinguish the main problems faced by Gazprom in the delivery of oil products from oil depots to gas stations:

1) insufficient satisfaction of customer demand;

2) high cost of delivery of petroleum products, making a delivery to third-party wholesale buyers non-competitive in price;

3) inflexibility of the present distribution model.

4.4 Data collection

Main sources of data

Since the model considers a network that is completely managed by the Gazprom company, most of the database was taken from Gazprom's website, as well as during an interview with a logistics manager from the supply chain department of Gazprom. There were two main sources of data collection needed to complete this work, namely interviews with the manager of the logistics department and secondary data collected independently.

Interviews

Two interviews were conducted with the manager of the planning and logistics department of Gazprom. These interviews gave an insight into the logistics activities of Gazprom in Russia as a whole, as well as in more detail in the region under consideration, and discussed the problem faced by the company and options for its solution. General data about the routing performed by the company was also provided. In addition, the company provided all the necessary data upon request, and also conducted additional consultations.

Secondary data

Secondary data for this study was obtained using the Google API service, where, by specifying the coordinates of the points, it is possible to find the exact distances between the objects in the distribution network and create a distance matrix that is used later in the model.

Data cleaning was also carried out later, which made it possible to fill in the missing values, detect and remove unnecessary data and outliers. This helped to clearly define what constraints will be applied to the model and what required data will be used in it.

4.5 Main assumptions

This real problem is addressed in the following assumptions:

1) Demand is assumed to be deterministic and forecasted. The model will not be affected by fluctuations and uncertainty in demand and supply of petroleum products;

2) The planning period is made up of the delivery of 10 days;

3) The homogeneous fleet of vehicles is used for the transportation of oil products. It is assumed that the vehicles are equipped with flow meters, which allow splitting the loads;

4) The cost of delivering gasoline per unit of distance is known and varies depending on the delivery area and mode of transport (own fleet or third-party);

5) Stations can be visited several times during the same day and around the clock, as it is assumed that a vehicle can always deliver oil products to the station and there are no time windows;

6) No consideration is given to the time spent resting and changing drivers;

7) Same truck can be used for multiple trips;

8) There is only one type of delivered petroleum product - gasoline;

9) There are two types of vehicles: own Gazprom's fleet and the 3PL fleet. Each depot has a certain number of vehicles of each type;

10) The speed of fuel trucks is constant;

11) After the fuel truck arrives at the depot or gas station, it takes time to load or unload oil products, and the loading and unloading time is constant;

12) The transshipment capacity of the depot significantly exceeds the demand of customers and therefore there is no limit on the amount of gasoline available for delivery to the customers;

5 Mathematical Model formulation

This chapter aims to present a developed mathematical model. A mixed-integer linear model was created in order to solve the optimization problem of choosing the most optimal variant for the development of a supply chain network. When solving transportation optimization problems, one should take into account various restrictions regarding both customers and the routes along which goods must be delivered to customers.

Objective and requirements of model formulation:

The objective of the planning task considered in this thesis is to create a plan for the replenishment of gas stations, taking into account the requirements that are presented below.

1) A route plan must be created.

The result of the planning methods should be a vehicle replenishment plan for each trip, which shows drivers how many liters of fuel to load into the vehicle, as well as the amount of product to be delivered to each station.

2) The plan must be completed within the planning horizon.

Although customers do not set strict delivery limits, all customers must be visited and their demands satisfied within 10 days.

3) Solution must be feasible.

The solution must be feasible under the applicable capacity and time constraints.

Problem description:

Multi-objective - has two objectives: 1) reduce transportation costs and 2) reduce operational costs connected with the usage of different types of vehicles;

Multi-depot - vehicles service customers from a set of depots;

Multi-vehicle - two types of vehicles;

Homogeneous fleet - capacity of each vehicle is the same;

Fixed number of vehicles - number of available vehicles is fixed for each depot;

Deterministic demand - demand is considered to be deterministic and will not be changed;

Split delivery - vehicles are allowed to split the load between several customers;

Multiple trip - vehicles can make multiple trips within a 10 day planning horizon.

The mathematical model includes:

1) a set of variables, acting on which the system can be improved;

2) parameters that affect a mathematical object's output but are treated as constants and are provided by the case study; many parameters will be included in the model to make it more realistic and valuable when calculating travel times and costs between depots and gas stations.

3) an objective function that allows finding the best option from a set of possible ones while minimizing total transportation cost;

4) constraints (system of restrictions) imposed on variables. These conditions follow from the nature of the logistics network, the capacity of vehicles and facilities, the limited resources available, the need to meet fully needs of customers, and the conditions of production and technological processes. Mathematically, constraints are expressed as equations and inequalities. Their totality forms the domain of admissible solutions.

The mathematical model presented in the research of Hanum et al. (2019) was chosen as the basis for developing the model for this case as it considers the multi-trip split delivery problem. Several necessary extensions have been made to customize the model according to the real case of Gazprom. The problem of oil replenishment is related to the logistics of delivering oil products to a set of gas stations in such a way that the requirements of customers are met in accordance with the operational capabilities of the carrier, while minimizing transportation costs. To facilitate the formulation of the mathematical model, the following sets have been used throughout the thesis. Let $G = (N, E)$ be a graph, where N is a set of all nodes in the network, consisting of $\{N^D, N^C\}$ where $N^D = \{1, 2, ..., n\}$ is a set of all depots where n is a number of depot nodes, $N^C = \{n+1, ..., n+m\}$ is a set of customers where m is a number of all customer nodes, and edge set is $E = \{(i,j) : i \neq j \text{ and } i,j \in N\}$. In addition, V is a set of vehicles. Delivery is performed by a homogeneous fleet of vehicles V which are stationed at the certain supply depot. Each vehicle $v \in V$ has the same capacity Q. Each customer $i \in I$ has a non-negative demand q_i for gasoline and depots has no demand. R is a set of trips where upper bound on the number of trips for vehicle v should make is calculated as $\frac{\sum_{i \in N^C} q_i}{|V|Q}$ where $|V|$ is a total number of vehicles. Between any pair of customers and depots $i,j \in N$, a positive travel distance d_{ij} is specified in a matrix as well as a travelling cost matrix for 3PL vehicles depending on zones of transportation. In addition, vehicle cost c_v^V is used to calculate the cost of usage different fleets.

5.1 Indices

i, j - nodes indices

v - vehicle index

r - trip index

5.2 Sets

N^C: set of demand nodes, network of filling station where gasoline is sold to end consumers;

N^D: set of depots where gasoline is stored and from where it will be delivered to the network of filling stations;

N: set of all nodes in the distribution network including depots;

N_i^V: set of vehicles assigned to depot $i, i \in N^D$;

V: set of all vehicles (fuel trucks) used for delivery of gasoline from set of oil depots to the network of filling stations, $V = \cup_{i \in N^D} N_i^V$;

R: set of trips, a sequence of customers to visit, starting and ending at a depot;

5.3 Parameters

Q: capacity of vehicles;

c_v^V: vehicle's costs;

d_{ij}: transportation distances in km between nodes i and j, where $i, j \in N, i \neq j$

c_{ij}^T: traveling cost for third party carriers;

q_i: customer's demand;

T^u: time spent on unloading of vehicle at filling station in hours;

T^l: time spent on loading or restocking of vehicle at the depot in hours;

H: total amount of hours within planning horizon;

S: speed of vehicle in kmh;

5.4 Variables

x_{ijvr}: binary decision variable that indicates whether vehicle travels from nodes i to j;

U_{ivr}: variable used for subtour elimination, shows the position of node $i \in N^C$ in the route;

Z_{vr}: binary variable that shows if vehicle v is operated at trip r;

L_{ivr}: variable that indicates amount of delivered fuel to node i by vehicle v on a trip r;

5.5 Objective function

The objective function (1), presented in a linear form with the same weights of objectives, consists of summation of cost that is amounted to all used vehicles and transpiration cost that depends on the total distance travelled between customers and depots and amount of products delivered.

$$\min \sum_{v \in V} \sum_{r \in R} c_v^V Z_{vr} + \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \sum_{r \in R} c_{ij}^T d_{ij} x_{ijvr} L_{ivr} \tag{1}$$

5.6 Constraints

Research based on real problems must take into account many constraints. All logistics facilities have their own technical characteristics and limitations, such as maximum transshipment volumes, storage tank volumes, and vehicle capacity. Therefore, the throughput characteristics of objects, as well as throughput restrictions for various modes of transport, significantly affect the overall throughput of the logistics network.

$$\sum_{j \in N^C} x_{ijvr} = Z_{vr}, v \in N_i^V, i \in N^D, r \in R \tag{2}$$

$$\sum_{j \in N^C} x_{ijvr} = 0, v \notin N_i^V, i \in N^D, r \in R \tag{3}$$

$$\sum_{i \in N^C} x_{ijvr} = Z_{vr}, v \in N_j^V, j \in N^D, r \in R \tag{4}$$

$$\sum_{i \in N^C} x_{ijvr} = 0, v \notin N_j^V, j \in N^D, r \in R \tag{5}$$

$$x_{ijvr} \leq Z_{vr}, i \in I, j \in N^C, v \in V, r \in R \tag{6}$$

$$x_{ijvr} = 0, i, j \in N^D, v \in V, r \in R \tag{7}$$

$$x_{iivr} = 0, i \in N, v \in V, r \in R \tag{8}$$

$$U_{ivr} - U_{jvr} + n x_{ijvr} \leq n - 1, i \in I, j \in N^C, v \in V, r \in R \tag{9}$$

$$\sum_{i \in N} \sum_{v \in V} \sum_{r \in R} x_{ijvr} \geq 1, j \in N, i \neq j \tag{10}$$

$$\sum_{i \in N} x_{isvr} - \sum_{j \in N} x_{sjvr} = 0, s \in N, v \in V, r \in R \tag{11}$$

$$L_{ivr} \leq q_i \sum_{j \in N} x_{ijvr}, i \in N^C, v \in V, r \in R \tag{12}$$

$$\sum_{v \in V} \sum_{r \in R} L_{ivr} = q_i, i \in N^C \tag{13}$$

$$\sum_{i \in N^C} L_{ivr} \leq Q, v \in V, r \in R \tag{14}$$

$$\sum_{j \in N^C} x_{ijvr} \geq \sum_{j \in N^C} x_{ijvr+1}, i \in N^D, v \in V, r \in R \tag{15}$$

$$\sum_{r \in R} (\sum_{i \in N^D} \sum_{j \in N^C} x_{ijvr} T^u + \sum_{i \in N} \sum_{j \in N^C} x_{ijvr} T^l + \sum_{i \in N} \sum_{j \in N} \frac{x_{ijvr} d_{ij}}{S}) \leq H, v \in V \tag{16}$$

$$\sum_{i \in N} \sum_{v \in V} \sum_{r \in R} x_{ijvr} \leq \frac{q_i}{Q}, j \in N^C \tag{17}$$

$$x_{ijvr} \in \{0, 1\}, i \in N, j \in N, v \in V, r \in R \tag{18}$$

$$Z_{vr} \in \{0, 1\}, v \in V, r \in R \tag{19}$$

$$L_{ivr} \geq 0, i \in N, v \in V, r \in R \tag{20}$$

$$U_{ivr} \geq 0, i \in N, v \in V, r \in R \tag{21}$$

Constraint (2) allows vehicles to leave the depot to which they are allocated. Constraint (3) ensures that all vehicles can not leave the depot to which they are not assigned. Constraint (4) lets vehicles return back to the initial depots. Constraint (5) guarantees that vehicles can not return to the depots to which they are not assigned. Constraint (6) allows vehicles not to leave the depot if they are not needed, so not all vehicles can be used on a trip. Constraint (7) guarantees that there are no trips between sets of depots. Constraint (8) does not allow trips between the same customers. Constraint (9) helps to avoid subtours. Constraint (10) allows a customer to be visited more than once by more than one vehicle during different trips. Constraint (11) ensures trip continuity by providing a rule that as soon as the vehicle reaches the node, it must leave that location. Constraint (12) specifies that the quantity of products delivered to a customer on each trip does not exceed its demand. Constraint (13) provides full satisfaction of each customer's demand. Constraint (14) makes sure that the loading of each vehicle does not exceed its capacity. Constraint (15) is defined to ensure the continuity of trips at each node, to ensure that the trip r is performed before the trip $r+1$. Constraint (16) ensures that delivery is performed during the given planning horizon for each vehicle as a summation of time spent on unloading at each filling station, loading or restocking at the depot and travel time between nodes. Constraint (17) limits the number of visits to filling stations by vehicles to satisfy customer demand and the upper bound is calculated as the ratio of the customer's demand to the vehicle capacity. Constraints (18 - 19) are used to define binary variables, and constraints (20 - 21) enforce the variables to be non-negative.

6 Solution method

This section presents solution methods to solve formulated mathematical model.

The deterministic MILP is created for planning the real-world scenario of the transportation network between oil depots and fuel stations to satisfy demand, while minimizing total transportation costs over a specified geographic region in Russia, including penalties for unsatisfied demand. The model includes current network design with routing planning for a 10 day planning horizon. The model considers the location of the oil depots and gas stations, customer's demand, the different zones of transportation, as well as the modes of transportation to move the products from depots to the demand nodes when designing the supply chain.

It turned out from the results of the experiments, for large instances of the problem, with 66 filling stations network and 6 depots, MILP could not be used to find solutions. Even when the calculation time limit was set to 4-5 hours, an out of memory error "CPLEX Error 1001: Out of memory" was thrown after approximately 5000 seconds without providing any solution. Thus, the solution for MILP models can only be found by the solver for cases with a relatively small number of gas stations within a network, which makes it impossible to compare the results obtained after clustering with the results without it due to too many demand nodes in the Gazprom's network.

6.1 Clustering

The first step of each phase is clustering in order to dispatch the original problem to subproblems that can be determined with a limited computational system. The number of clusters is an important aspect to consider when using clustering since the number of clusters impacts the number of customers in each cluster, altering the total solution of the problem after grouping. An increase in the number of clusters leads to a reduction in the number of filling stations in the cluster, which typically leads to better results, and this is a critical factor in assisting in the reducing of the considering network's scale. The problem was clustered using two different approaches.

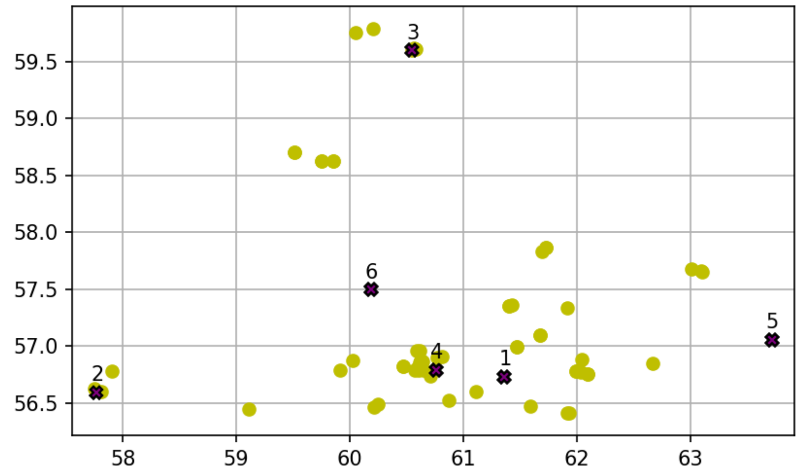

Figure 6: Map of filling stations (yellow dots) and depots (purple crosses).

The first approach of clustering considers the division of gas stations into a number of clusters equal to the number of operating depots. Each cluster includes a single depot, which is a centroid. In this case, since the model now considers only one depot in each cluster, constraints (2 - 5) and (7) related to the multi-depot problem can be omitted. This clustering was performed with the help of the first part of the hybrid heuristic used in the research of Mirabi et al. (2010) where authors were assigning customers to depots as a grouping problem depending on the distance between customers and depots. In this thesis, there are multiple oil depots and customers (filling stations), and each customer must be assigned to one specific depot, as the goal here is to simplify the problem and make it more realistic with regard to a real-life problem. For example, each customer, say c_i, must be assigned to exactly one depot d_j.

The clustering choice is fully based on the following calculation of euclidean distance $d_{ci,dj}$ between customer c_i and depot d_j, where $Cluster_{cidj}$ is a binary variable which specifying if a customer c_i with coordinates (x_{ci}, y_{ci}) from a set N^C assigned to a specific depot d_j with coordinates (x_{di}, y_{di}) in a set N^D:

$$\sum_{d_j \in N^D} Cluster_{cidj} = 1, c_i \in N^C \tag{22}$$

$$d(c_i, d_j) = \sqrt{(x_{ci} - x_{dj})^2 + (y_{ci} - y_{dj})^2} \tag{23}$$

$$\text{if } d(c_i, d_j) \leq d(c_i, d_{j+1}), \text{ assign } c_i \text{ to } d_j \tag{24}$$

$$\text{if d}(c_i, d_j) \geq d(c_i, d_{j+1}), \text{ assign } c_i \text{ to } d_{j+1} \tag{25}$$

$$\sum_{c_i \in N^C} Cluster_{cidj} \leq \frac{|N^C|}{|N^D|} \tag{26}$$

$$Cluster_{cidj} \in \{0, 1\}, c_i \in N^C, d_j \in N^D \tag{27}$$

Constraint (22) specifies that every filling station has to be assigned to the cluster. Formula (23) represents the calculation of euclidean distance between customer c_i and depot d_j. Rules (24) and (25) provide for the assigning of customers to the clusters according to the euclidean distance between them and depots. Customers should be assigned to the nearest depot. Constraint (26) specifies the upper bound of the number of customers in each depot, respectively as a ratio of the number of all clients in the network to the number of all centroids (depots) in order to distribute clients across clusters evenly. Constraint (27) defines binary variable $Cluster_{ij}$ where 1 if customer c_i belongs to cluster with depot d_j, 0 otherwise.

In the second approach, the division of the problem into three clusters, with two depots inside each of them, is considered. It was done with the help of k-means clustering in order to find new optimal locations for the dummy centroid. K-mean splits the set of elements into a predetermined number of clusters. The action of the algorithm is such that it seeks to minimize the distance from elements to cenroids. The main idea is that at each iteration the center of mass is recalculated for each cluster obtained at the previous step, then the input vectors are divided into clusters again in accordance with which of the new centers turned out to be closer according to the chosen metric. The algorithm terminates when no cluster changes occur at some iteration. When new dummy centroids are found, depots which are the closest to them are grouped into the same cluster. Next, the same grouping algorithm as in the first approach is applied in order to split customers into equal clusters.

6.2 Routing modeling

The second step in each phase, which goes after clustering, is intended to generate routes for each cluster in the model separately one by one for both the variants of clustering mentioned above and compare results. The mathematical model proposed in the chapter 5 was used to solve routing and scheduling petrol station replenishment problem.

7 Computational experiments and results

This section presents experiments were performed and discusses obtained results. The problem is divided into two phases, namely, the first one considers the problem when all depots in the network are able to operate, and the second one considers the problem when one depot is out of service and there is a need for gasoline flow redistribution. Both phases include clustering of customers and depots using two approaches and their further comparison when implementing the model. In addition, model testing on problems with different scales was performed in order to check if the model can be used for other cases.

7.1 Experimental environment

Experiments are performed on a computer with a 1.60 GHz quad-core processor and 8 GB of RAM. In the MILP model, routes are built using a sequence of binary variables x_{ijvr} representing a vehicle v moving along the trip r from nodes i to node j and the distance matrix between different locations (including depots) is obtained by manually with the help of Google API.

Mathematical models are implemented in Python with the help of PyCharm Integrated Development Environment, and MILP models are solved using the CPLEX solver. Optimizer version identifier: 20.1.0.0. CPLEX is a software package (solver) designed to solve linear and quadratic programming problems, including integer programming. The CPLEX package is currently being developed by IBM.

7.2 First phase

7.2.1 Clustering

As a result of the 1st clustering approach, the filling stations were evenly grouped into 6 clusters, depending on their geographical location and distances between customers and depots, which are the centroids of clusters (see Figure 7 and Table 3).

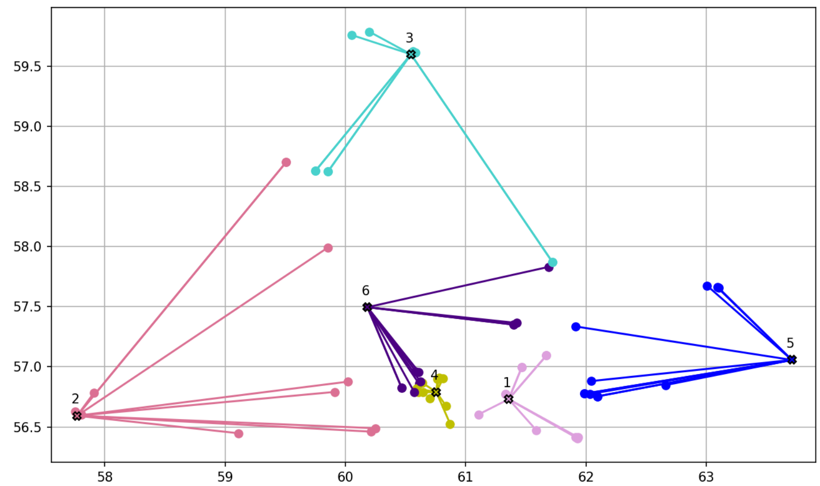

Figure 7: Map of clusters with 11 filling station in each.

1st cluster	2nd cluster	3rd cluster	4th cluster	5th cluster	6th cluster
11	11	11	11	11	11

Table 3: Number of clients in each cluster.

Regarding the second approach, the data set for the k-means clustering algorithm was used as input, including the coordinates: latitude and longitude of 66 clients. As a result of k-means clustering, three new locations for the centroids were proposed and can be seen in Figure 8 (yellow crosses are the dummy cenroids). The depots which are the closest to the determined by k-means centroid are grouped into the same cluster (See Figure 9): new dummy centroids (blue icons) are located between depots 1 and 5, 2 and 4, 3 and 6, so new clusters include exactly these pairs of depots. Next, these new coordinates of centroids were used to assign customers to clusters with the help of the same grouping method used before, which is based on euclidean distances between depots and customers. As a result of clustering, all clients were split into 3 equal groups of 22 filling stations each and attached to clusters (See Figure 10 where different colors represent different clusters).

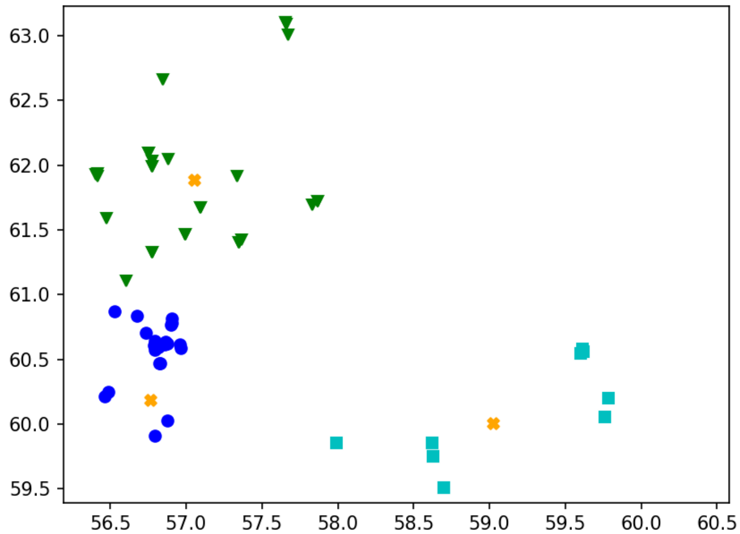

Figure 8: K-means clustering.

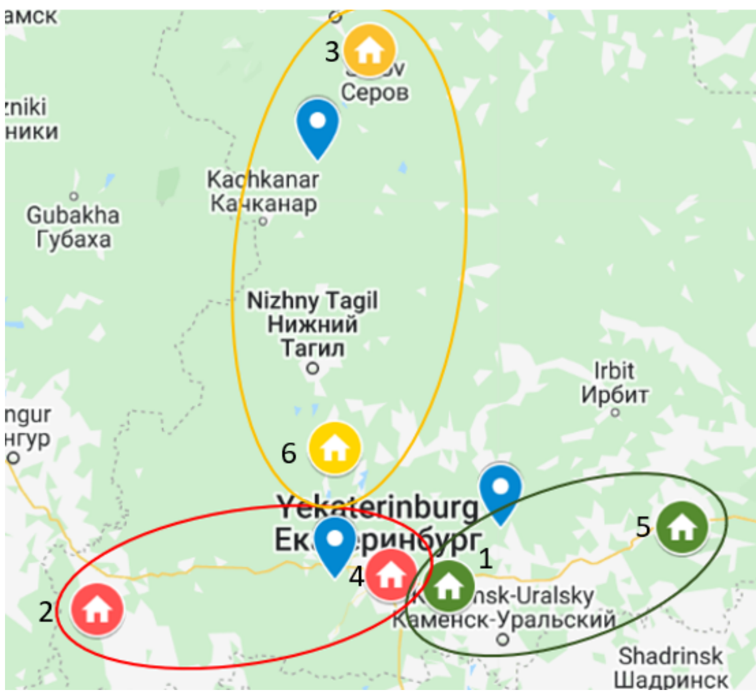

Figure 9: Map of created clusters.

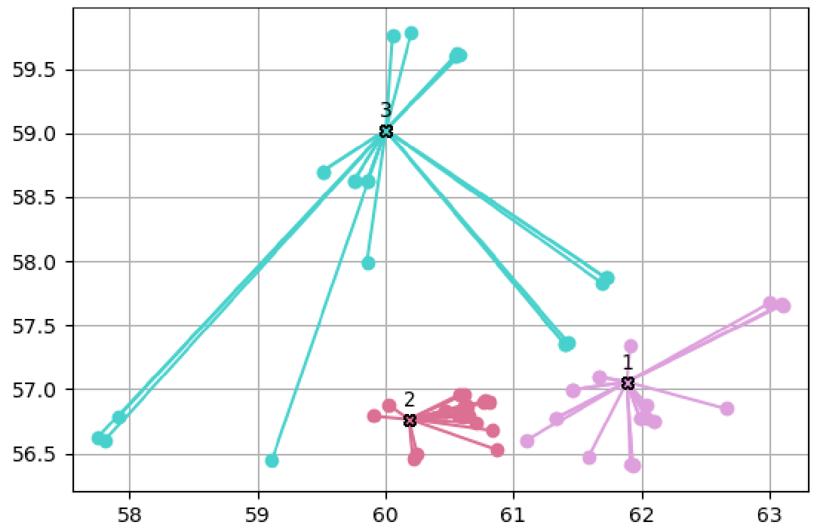

Figure 10: Map of clusters after K-means.

To sum up, two clustering options have been obtained to solve the problem of assigning clients to the depots. The classification of filling stations into homogeneous groups allows the creation of models for each cluster, which increases the accuracy of studies. Next, it is necessary to figure out which of the options is actually the most admissible and can make it possible to reduce the company's transportation costs for the delivery of gasoline from the depots to the gas stations located in the clusters.

7.2.2 Routing modeling

The model for every cluster was run for 5000 seconds. Having studied and compared the results, it turned out that the second clustering option, which includes two depots in each cluster, leads to worse optimization results for the same run time of the model. More precisely, the total cost of this clustering option is 2,695,543.7 units with the total travel distance equal to 77,782 km, an average optimization gap is 29.19 %. At the same time, the final cost of the clustering option with 6 clusters and 1 depot in each is 2,607,214.4 units, which is 3.39 % cheaper, with the final distance for all vehicles for all trips - 74,248.9 km, which is 4.75 % shorter, an average optimization gap is 15.21 %. This difference in the total cost and travelled distances can be explained by a larger number of clients in the clusters. Namely, there are 22 clients and 2 depots grouped together in each cluster with the help of the second approach, meanwhile, the maximum number of clients in the first clustering is 11. A larger number of clients in a cluster leads to the complicity of the optimization and increased optimization time due to the larger scale of the problem and greater number of available route options. In addition, it is noticeable that the 2nd clustering variant takes more time and more trips to deliver gasoline to the network of filling stations but still delivery is performed within the planning horizon and the time frames are not violated. Thus, the clustering variant obtained using the option with 1 depot in each cluster is the optimal one.

Comparative clustering results are shown in Table 4.

No. Cluster	6 clusters	3 clusters
Transportation cost, units		
1st Cluster	209,636.3	610,833.0
2nd Cluster	614,201.6	955,984.1
3rd Cluster	990,162.6	1,128,726.5
4th Cluster	130,254.5	
5th Cluster	330,749.7	
6th Cluster	332,209.5	
Total	2,607,214.4	2,695,543.7
Transportation distance, km		
1st Cluster	5,565.7	18,728.0
2nd Cluster	16,711.5	23,801.2
3rd Cluster	28,656.5	35,252.8
4th Cluster	3,242.0	
5th Cluster	10,291.6	
6th Cluster	9,781.5	
Total	74,248.9	77,782

No. Cluster	6 clusters	3 clusters
Max travel time, h		
1st Cluster	54.1	89.5
2nd Cluster	106.7	114.9
3rd Cluster	162.0	189.2
4th Cluster	46.9	
5th Cluster	69.3	
6th Cluster	77.7	
Max number of trips per vehicle		
1st Cluster	11	12
2nd Cluster	11	13
3rd Cluster	12	13
4th Cluster	13	
5th Cluster	10	
6th Cluster	11	
Total number of trips		
1st Cluster	44	85
2nd Cluster	43	97
3rd Cluster	46	90
4th Cluster	49	
5th Cluster	38	
6th Cluster	41	
Total	261	272
Gap, %		
1st Cluster	14,22	27,67
2nd Cluster	19,07	30,34
3rd Cluster	11,09	29,58
4th Cluster	18,12	
5th Cluster	16,07	
6th Cluster	13,19	

Table 4: Comparative clustering results.

7.3 Second phase

7.3.1 Clustering with depot on reconstruction

The next phase considers the problem of closing one of the depots for reconstruction for 2 years, therefore this depot must be disconnected from a set of depots during this period. Any depot can be closed, but according to information received from Gazprom, it is the 4th depot that should undergo reconstruction soon, so there should be a redistribution of gasoline flows that were delivered to customers in the 4th cluster from this depot.

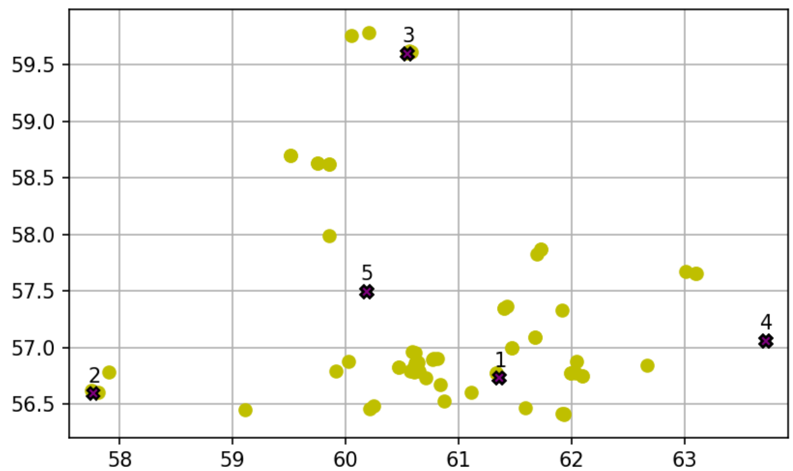

Figure 11: Map of filling stations (yellow dots) and depots (purple crosses) without closed depot.

The first step is to perform re-clustering in order to re-distribute the clients among depots. As before, two same variants of clustering are considered. The first approach considers dividing the set of customers into 5 clusters with 1 single depot and up to 14 filling stations in each. The same assigning algorithm is used as in the first customer's grouping implementation. According to the results obtained, the filling stations were divided into 5 clusters, with 14 clients in each, except for the 2nd cluster - there are 10 clients (See Figure 12 and Table 5).

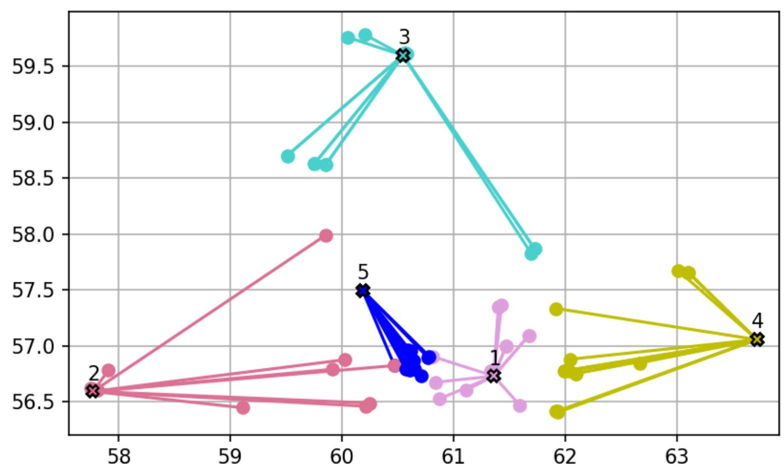

Figure 12: Map of clusters with up to 14 filling station in each.

1st cluster	2nd cluster	3rd cluster	4th cluster	5th cluster
14	10	14	14	14

Table 5: Number of clients in each cluster.

Next, applying the second clustering approach with several depots in each cluster, k-means clustering was used again to find dummy centroids locations. Since the input of customers' coordinates and the number of clusters do not change, the coordinates for dummy depots remain the same as in the first phase. The scheme for grouping depots into clusters stays unchanged - the depots closest to the determined by K-means dummy centroids are combined into the same cluster. However, now due to the fact that one depot is closed and the number of depots is odd, one cluster has only a single depot in it and clusters now include other pairs of depots, namely, 1st cluster: 1 and 4; 2nd cluster: 2 and 5; 3rd cluster: 3 (See Figure 13).

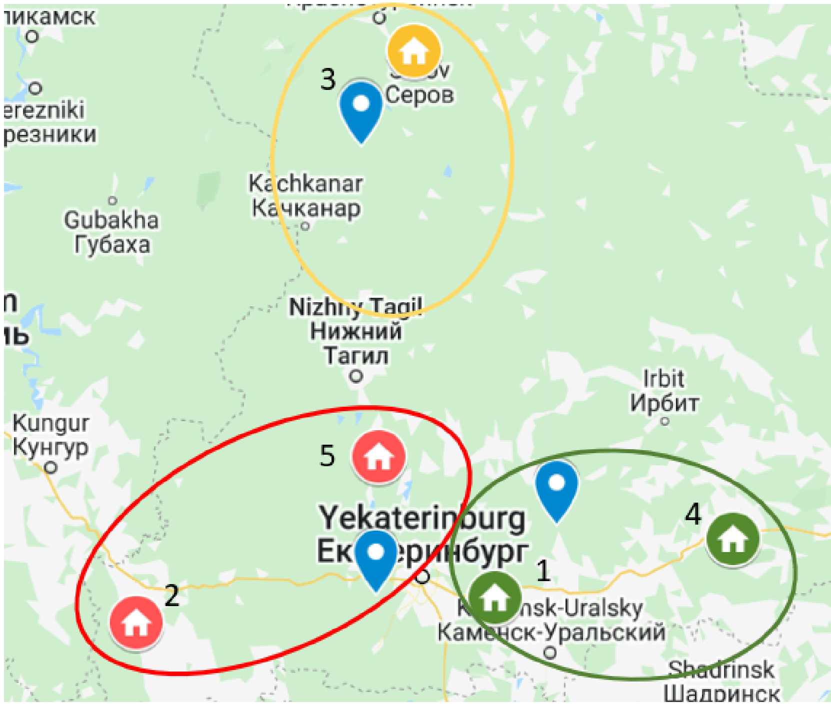

Figure 13: Map of clusters without closed depot.

Now the filling stations that were included in the 4th cluster are distributed among the depots that remain open and are the closest to the 4th one, and now gasoline will be delivered from them. Later routing testing can provide a more precise analysis of two clustering approaches and find the best one.

7.3.2 Flow redistribution modeling

Having received two clustering options, it is necessary to check which of them is the best for the redistribution of gasoline flows from the depots to the gas station in the event that the 4th depot is closed for reconstruction. It should be mentioned that due to the fact that the 4th depot is closed, 4 vehicles which were initially assigned to it now continue operating in other clusters. Namely, when applying the first variant of clustering vehicles are evenly split among four operating depots, and in the case of the second variant of clustering, all vehicles are assigned to the 3rd depot according to the task of Gazprom as this depot has to supply the whole cluster.

The obtained results (see Table 6) show that the second variant of clustering using the 3 clusters approach gives worse results compared with the first one. The total cost for the delivery of gasoline from the depots to the gas station network for all 3 clusters, in this case, amounted to 4,351,082.7 units with a total length of all routes of 113,356.4 km (an average optimization gap is 26.0%) while delivery along the routes obtained using the 5 clusters option is cheaper for 34.83 % and shorter for 33.07% (3,043,444.6 units and 85,918.3 km respectively, an average gap is 16.53 %). The main part (52.07 %) of the total costs in the second clustering variant is the third cluster, this is due to the fact that the depot located in it serves customers located far away from it (See figure 10), which significantly increases the cost of delivery. In addition, as before, the second variant requires more trips to deliver gasoline to the filling stations.

No. Cluster	5 clusters	3 clusters approach
Transportation cost, units		
1st Cluster	328,202.7	832,233.0
2nd Cluster	533,695.2	1,253,101.3
3rd Cluster	1,417,002.1	2,265,748.4
4th Cluster	490,666.7	
5th Cluster	457,304.1	
Total	3,226,871.0	4,351,082.7
Transportation distance, km		
1st Cluster	7,465.6	21,892.8
2nd Cluster	14,219.4	29,590.8
3rd Cluster	36,927.5	61,872.8
4th Cluster	14,295.2	
5th Cluster	12,271.7	
Total	85,179.4	113,356.4
Max travel time, h		
1st Cluster	64.5	85.3
2nd Cluster	82.9	105.6
3rd Cluster	174.0	187.8
4th Cluster	85.8	
5th Cluster	87.8	

No. Cluster	5 clusters	3 clusters approach
Max number of trips per vehicle		
1st Cluster	12	12
2nd Cluster	9	13
3rd Cluster	12	13
4th Cluster	10	
5th Cluster	15	
Total number of trips		
1st Cluster	56	88
2nd Cluster	41	97
3rd Cluster	57	89
4th Cluster	48	
5th Cluster	58	
Total	260	274
Gap, %		
1st Cluster	20.41	28.82
2nd Cluster	14.98	29.85
3rd Cluster	13.79	19.37
4th Cluster	19.08	
5th Cluster	14.39	

Table 6: Comparative clustering results with redistribution of flow.

According to the results obtained, the model is able to redistribute gasoline flows in the event that one depot is closed for reconstruction within the planning horizon. If one of the depots is closed, customers are redistributed among the remaining depots, and the service continues.

By studying the overall results obtained, it becomes clear that the outcome received from clustering with a single depot in the cluster before and after redistribution of flow is better and more optimal compared with the approach where there are several depots in each cluster. This is related to the number of nodes in each cluster - the smaller the number of filling stations, the model can achieve a higher percentage of optimization due to the smaller problem scale for the same running time. When comparing the most optimal solutions received with a single depot in each cluster approach before and after the closure of one of the depots, it was found that the cost of delivery increased by 23.7 %, the distance of delivery by 14.7 % (see Table 7).

	6 Clusters	5 Clusters
Total transportation cost, units	2,607,214.4	3,226,871.0
Total transportation distance, km	74,204.8	85,179.4

Table 7: Comparative results without redistribution of flow and with it.

The results and comparisons of the calculations for each clustering option are shown in Tables 4 and 6. The best results of solving the mathematical model include proposed routes for vehicles (See Appendix: 10 Solutions), the volume of gasoline to be delivered to each specific client, the calculation of the maximum delivery time, as well as transportation costs and the distance to be travelled.

7.4 Model testing

Additional experiments were carried out in order to test the model on problems of different scales and with different combinations of clients and depots in it. The input for the following experiments was used from the same network of Gazprom but different variants of data were implemented. It should be noted that each depot has 4 vehicles assigned to it. The models were run for 3,000 seconds for each variant.

The results in Tables 8 - 10 show that the more nodes are included in the problem, the less optimization percentage can be achieved in a certain running time. By dividing a large-scale task into different variants of sub-tasks, the percentage of optimization changes over the same run time of the model. In addition, it is important to take into account that the percentage of optimization depends not only on the size of the problem (the number of customers and depots within the network) but also on the set of initial data (customers' demand) itself and the number of vehicles operating within the network. For instance, the more depots in the network, the more routing variants are available that increase the gap. Moreover, as total customer demand increases, the number of trips will increase as well, resulting in a worse optimization result. And regarding the number of vehicles serviced within the network: the fewer vehicles used, the more trips each vehicle needs to make to fully meet demand, leading to poorer optimization percentages.

The results of the experiments showed that the model can solve cases with 1, 2 and 3 depots and with the number of nodes in it up to 25. The problem, which considers the distribution network with 25 nodes was solved with the optimization gap equal to 96.59 %, and the problem with 27 nodes was not solved at all in the allotted time. Therefore, to solve problems of a larger scale, it is required to increase the running time of the model, split it into clusters, decrease the volumes of the input data (for instance, reduce customer demand), or assign more vehicles to serve customers.

1 depot & 10 customers	1 depot & 18 customers	1 depot & 22 customers
Gap, %		
10.98	23.03	27.12
Number of trips		
25	46	56
Max number of trips per vehicle		
7	12	15
Total cost, units		
154,962.9	297,243.3	404,264.1

Table 8: Comparative results for problems with 1 depot.

2 depots & 10 customers	2 depots & 18 customers	2 depots & 22 customers
Gap, %		
15.03	26.12	31.33
Number of trips		
25	46	57
Max number of trips per vehicle		
4	7	8
Total cost, units		
187,926.8	367,189.9	493,951.1

Table 9: Comparative results for problems with 2 depots.

3 depots & 10 customers	3 depots & 18 customers	3 depots & 22 customers
Gap, %		
19.83	25.93	32.01
Number of trips		
25	46	58
Max number of trips per vehicle		
3	5	6
Total cost, units		
242,202.5	483,612.5	961,541.8

Table 10: Comparative results for problems with 3 depots.

To conclude, testing proves that the model is able to find the best ways to deliver petroleum products from a depot to a set of customers, given various constraints. In addition, it is relatively flexible and can redistribute oil product flows, if necessary, as well as apply various options and combinations of clustering with 1, 2 and, if required, 3 depots in one cluster and a different number of filling stations in it.

8 Conclusion and future work

8.1 Concluding remarks

This thesis examines the Petrol Station Replenishment Problem using the distribution network of Gazprom in one of Russia's regions as an example. In order to improve the efficiency of the entire filling station replenishment system, this thesis presents the MILP model, which minimizes transportation costs as an objective function and takes into account a number of operational restrictions. The problem includes the clustering task and its subsequent analysis, which shows that the fewer nodes in the cluster, the more optimal the solution is. The outcome of this problem is a set of optimal routes within clusters where each route is associated with fuel trucks that leave and return back to their base. For a real-world case consisting of 66 gas stations and 6 depots with 24 fuel trucks, a detailed vehicle routing plan is optimized using this model. The set of all routes must satisfy customer demands and operational vehicle capacity constraints, minimizing the total cost of a trip as expressed by a complex generalized cost function and the entire travel distance. Total costs include transportation costs, as well as costs associated with the use of third-party and own fleet of vehicles. In addition, the flexibility of choosing between two modes of transport for transferring products adds to the model the decision on the mode of transport available for shipment of products. In addition, the model takes into account multiple trips and the split of delivery between customers. Another step forward compared to previous studies is that the proposed model is able to work with the redistribution of the flow of production in the event of the closure of one of the depots. Real data and real distances between nodes were used in the model in order to obtain high-quality results and make this research more valuable and applicable.

8.2 Further research

It can be concluded that the proposed approach to the solution can be considered very promising for optimizing the fuel supply process. However, its implementation requires further adjustment, extension, and adaptation, taking into account the requirements and limitations that exist in real systems. As a result, future research areas can be connected to the application of various techniques to get better solution and additional study of the problem, particularly in the context of the duration of the planning horizon, because fuel replenishment in actual systems is more uncertain than deterministic. Furthermore, the vehicle routing problems are NP-hard problems with strict computational time and space requirements, so the effectiveness of the solution is directly connected to the model's scale and the mathematical model is useful for achieving an optimal solution to a relatively small problem. This thesis has solved the problem complexity using clustering by dividing it into sub-problems and applying exact solvers to solve sub-problems. However, there exist meta-heuristics which can be applied to solve either full problems or sub-problems in a reasonable time. As a result, future research should focus on developing a highly efficient metaheuristic algorithm that can tackle more complicated vehicle scheduling problems in a reasonable amount of time.

Further studies, especially for this thesis, can be proposed as follows: (1) it is possible to include depot transshipment capacity or customer's demand into clustering; (2) to test clustering with different combinations of a number of clusters and number of filling stations in it in order to find the most optimal one; (3) to take into account the delivery of other petroleum products and their simultaneous delivery in different compartments of fuel tankers; (4) to use vehicles with different capacities and compartments; (5) to include the time for changing and resting drivers at the depot; (6) to apply real-time urban traffic speed analysis for more realistic findings; (7) to extend the planning horizon; (8) to consider using metaheuristics, so it can be used for more extensive data, and route formation can be faster.

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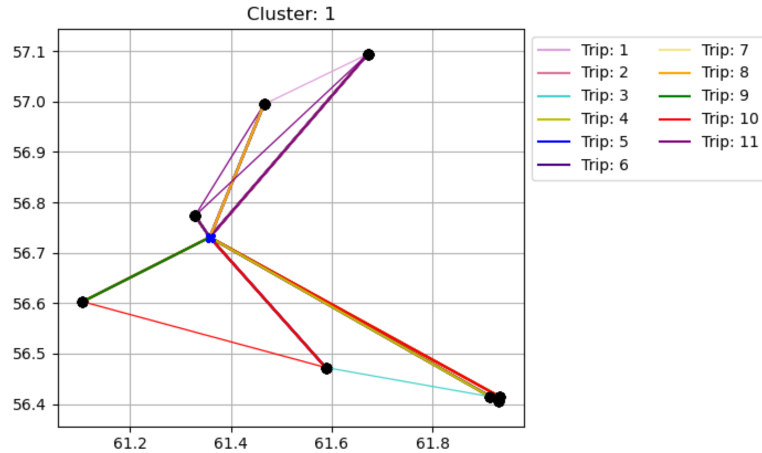
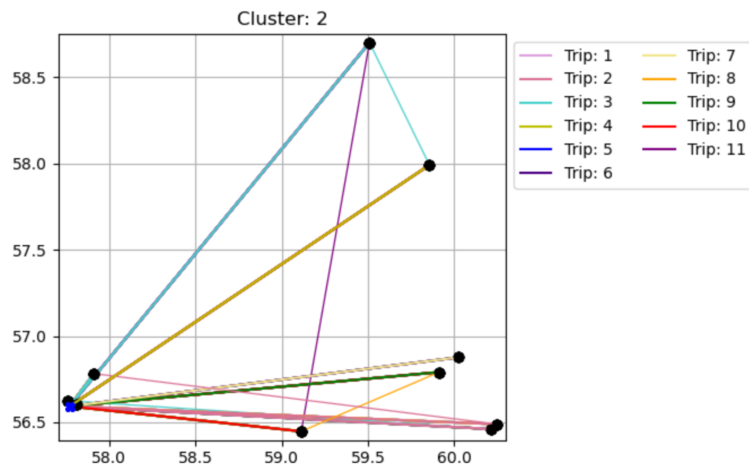
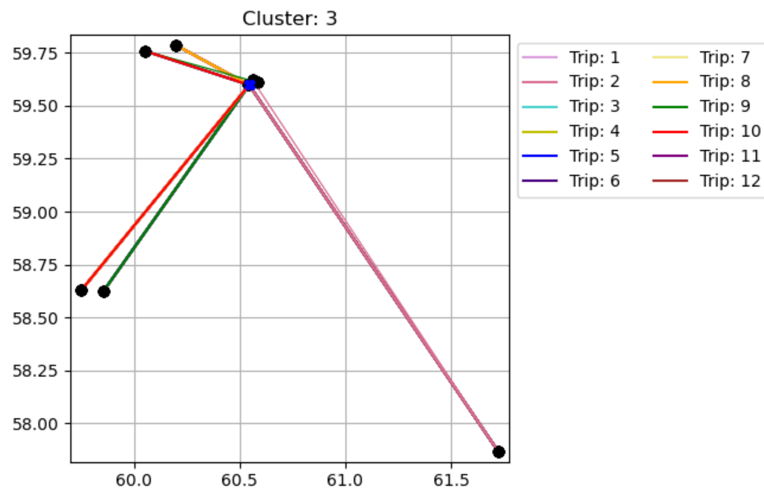
9 List of figures

Visualisation of the most optimal routes before and after fuel redistribution.



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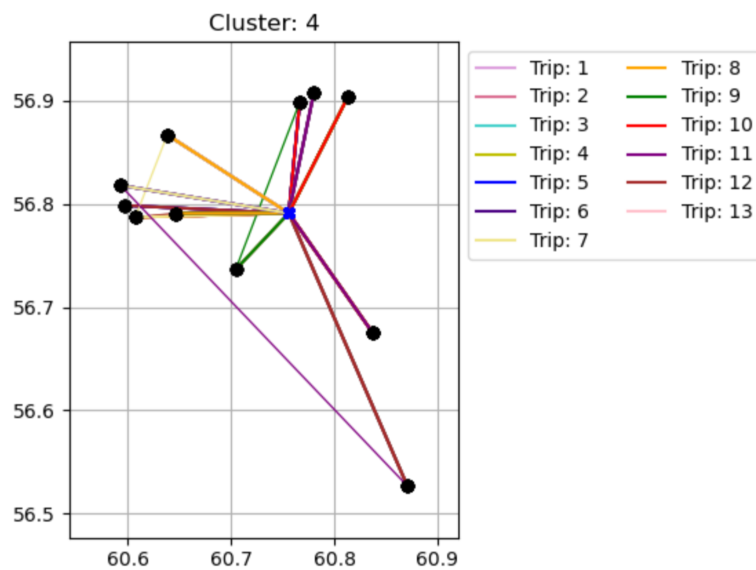
59.50
59.25
59.00
58.75
58.50
58.25
58.00
60.0
60.5
61.0
61.5
Trip: 1
Trip: 2
Trip: 3
Trip: 4
Trip: 5
Trip: 6
Trip: 7
Trip: 8
Trip: 9
Trip: 10
Trip: 11
Trip: 12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56.7
56.6
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60.7
60.8
60.9
Trip: 1
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Trip: 3
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Trip: 12
Trip: 13

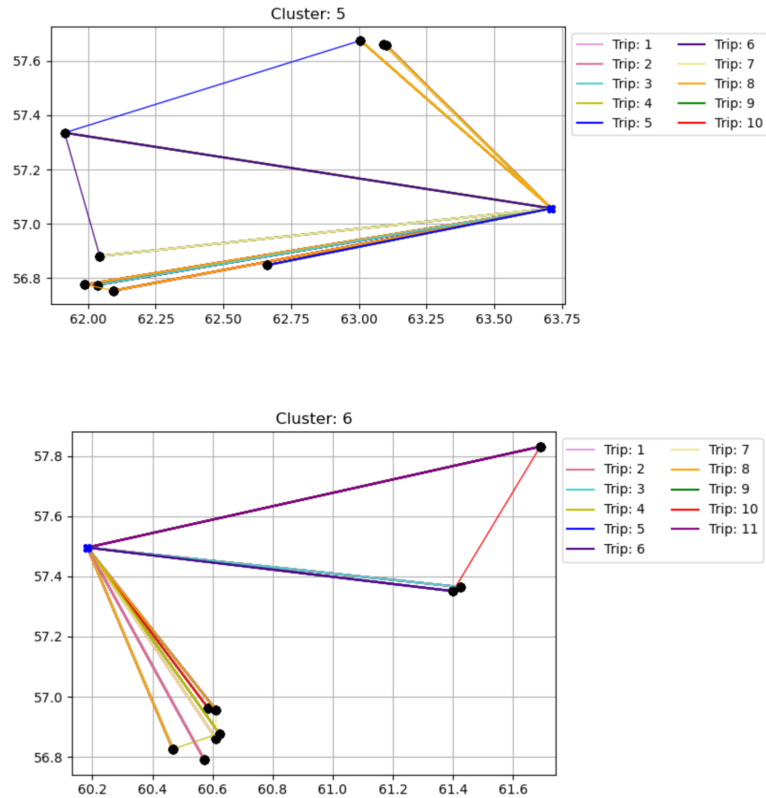
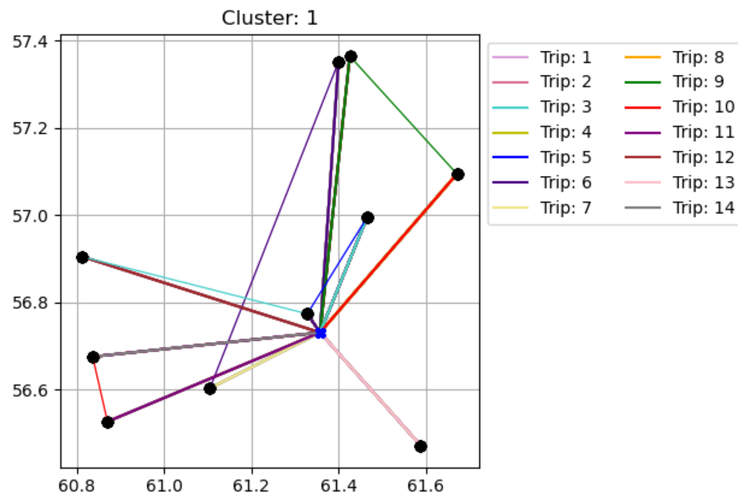


Figure 14: Visualisation of routes for 6 clusters variant.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57.2
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56.6
60.8
61.0
61.2
61.4
61.6
Trip: 1
Trip: 2
Trip: 3
Trip: 4
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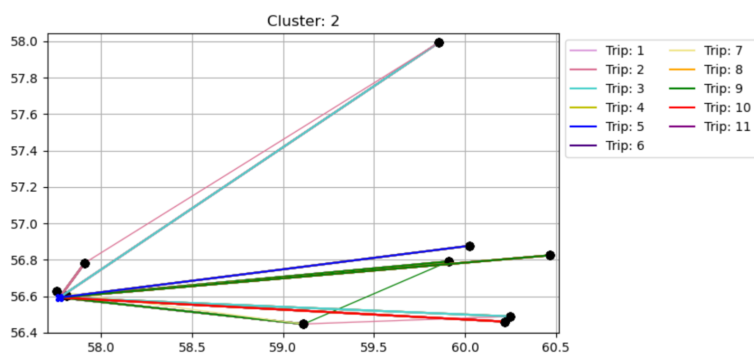
Trip: 13
Trip: 14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57.8
57.6
57.4
57.2
57.0
56.8
56.6
56.4
58.0
58.5
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59.5
60.0
60.5
Trip: 1
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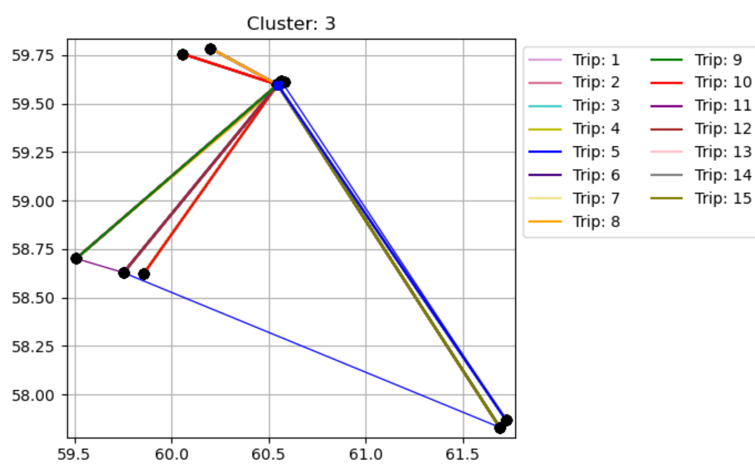
Trip: 10
Trip: 11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59.50
59.25
59.00
58.75
58.50
58.25
58.00
59.5
60.0
60.5
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61.5
Trip: 1
Trip: 2
Trip: 3
Trip: 4
Trip: 5
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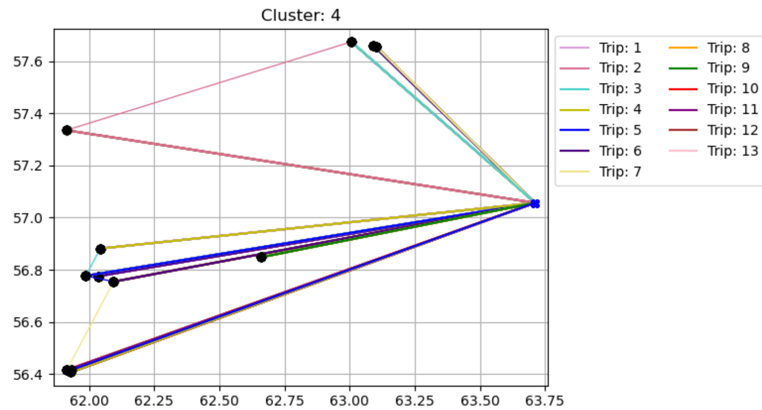

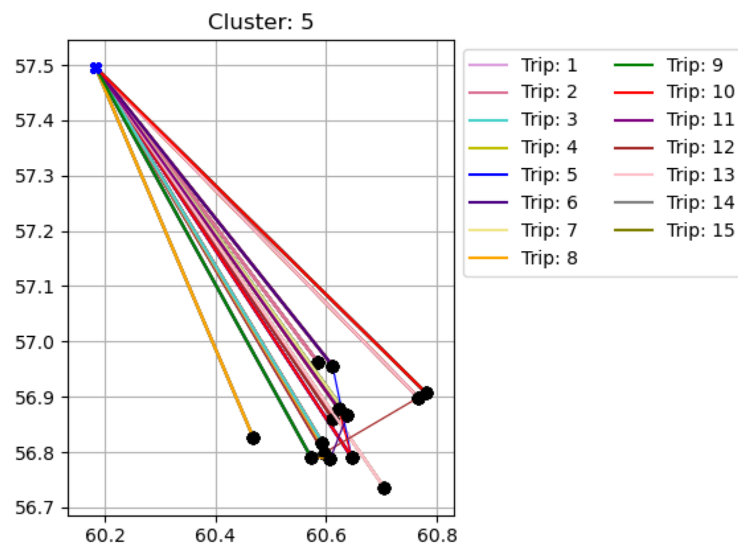

Figure 15: Visualisation of routes for 5 clusters variant.

10 Solutions

1st phase (6 clusters variant):

The solutions represent the plan of gasoline delivery with information about the amount of products (in tonnes) to be transported in the first brackets and the trip number in the second ones.

Vehicle: 1

1 $->$ 38 (21.4) (1) $->$ 1 (2) $->$ 63 (21.4) (2) $->$ 1 (3) $->$ 36 (18.8) (3) $->$ 1 (4) $->$ 60 (21.4) (4) $->$ 1 (5) $->$ 64 (21.4) (5) $->$ 1 (6) $->$ 64 (21.4) (6) $->$ 1 (7) $->$ 36 (21.4) (7) $->$ 1 (8) $->$ 36 (21.4) (8) $->$ 1 (9) $->$ 36 (21.4) (9) $->$ 1 (10) $->$ 51 (21.4) (10) $->$ 1 (11) $->$ 10 (21.4) (11) $->$ 1 (12) $->$ 10 (21.4) (12) $->$ 1 (13) $->$ 64 (21.4) (13) $->$ 1 (14) $->$ 60 (21.4) (14) $->$ 1 (15) $->$ 36 (15.3) (15) $->$ 10 (6.07) (15) $->$ 1 (15)

Distance of route = 2510.6

Vehicle: 2

1 $->$ 38 (21.4) (1) $->$ 1 (2) $->$ 60 (21.4) (2) $->$ 1 (3) $->$ 37 (21.4) (3) $->$ 1 (4) $->$ 65 (21.4) (4) $->$ 1 (5) $->$ 38 (21.4) (5) $->$ 1 (6) $->$ 36 (21.4) (6) $->$ 1 (7) $->$ 51 (21.4) (7) $->$ 1 (8) $->$ 37 (21.4) (8) $->$ 1 (9) $->$ 38 (21.4) (9) $->$ 1 (10) $->$ 51 (21.4) (10) $->$ 1 (11) $->$ 65 (21.4) (11) $->$ 1 (12) $->$ 60 (21.4) (12) $->$ 1 (13) $->$ 37 (21.4) (13) $->$ 1 (14) $->$ 65 (21.4) (14) $->$ 1 (15) $->$ 10 (21.4) (15) $->$ 1 (15)

Distance of route = 1907.7

Vehicle: 3

1 $->$ 50 (21.4) (1) $->$ 1 (2) $->$ 50 (21.4) (2) $->$ 1 (3) $->$ 50 (21.4) (3) $->$ 1 (4) $->$ 38 (17.6) (4) $->$ 1 (5) $->$ 49 (21.4) (5) $->$ 1 (5)

Distance of route = 219.3

Vehicle: 4

1 − > 49 (16.4) (1) − > 51 (5.0) (1) − > 1 (2) − > 50 (21.4) (2) − > 1 (3) − > 65 (16.8) (3) − > 1 (4) − > 49 (21.0) (4) − > 50 (0.3) (4) − > 1 (5) − > 50 (21.4) (5) − > 1 (6) − > 63 (16.8) (6) − > 1 (7) − > 63 (19.5) (7) − > 1 (8) − > 65 (16.4) (8) − > 64 (4.9) (8) − > 1 (9) − > 49 (18.6) (9) − > 1 (10) − > 37 (8.1) (10) − > 1 (10)

Distance of route = 905.9

Vehicle: 5

2 − > 13 (21.4) (1) − > 2 (2) − > 55 (21.4) (2) − > 2 (3) − > 9 (21.4) (3) − > 2 (4) − > 13 (21.4) (4) − > 2 (5) − > 21 (21.4) (5) − > 2 (6) − > 55 (21.4) (6) − > 2 (7) − > 9 (21.4) (7) − > 2 (8) − > 55 (9.86) (8) − > 72 (11.54) (8) − > 2 (9) − > 29 (21.4) (9) − > 2 (10) − > 11 (21.4) (10) − > 2 (11) − > 21 (21.4) (11) − > 2 (12) − > 29 (21.4) (12) − > 2 (13) − > 29 (21.4) (13) − > 2 (14) − > 70 (21.4) (14) − > 2 (14)

Distance of route = 6850

Vehicle: 6

2 − > 70 (21.4) (1) − > 2 (2) − > 29 (21.4) (2) − > 2 (3) − > 70 (21.4) (3) − > 2 (4) − > 9 (21.4) (4) − > 2 (5) − > 11 (21.4) (5) − > 2 (6) − > 72 (21.4) (6) − > 2 (7) − > 13 (21.4) (7) − > 2 (8) − > 72 (21.4) (8) − > 2 (9) − > 13 (21.4) (9) − > 2 (10) − > 13 (12.8) (10) − > 2 (11) − > 72 (21.4) (11) − > 2 (12) − > 11 (21.4) (12) − > 2 (13) − > 29 (21.4) (13) − > 2 (14) − > 23 (21.4) (14) − > 2 (14)

Distance of route = 5848.8

Vehicle: 7

2 − > 59 (21.4) (1) − > 2 (2) − > 23 (15.2) (2) − > 70 (6.1) (2) − > 2 (3) − > 59 (21.4) (3) − > 2 (4) − > 13 (20.0) (4) − > 2 (5) − > 68 (21.4) (5) − > 2 (6) − > 21 (16.0) (6) − > 2 (7) − > 59 (21.4) (7) − > 2 (8) − > 68 (21.4) (8) − > 2 (8)

Distance of route = 1392.9

Vehicle: 8

2 − > 68 (11.54) (1) − > 2 (2) − > 23 (18.5) (2) − > 9 (2.9) (2) − > 2 (3) − > 68

(21.4) (3) − > 2 (4) − > 11 (17.8) (4) − > 2 (5) − > 55 (14.9) (5) − > 2 (6) − > 23 (13.4) (6) − > 59 (1.2) (6) − > 2 (7) − > 11 (21.4) (7) − > 2 (7)

Distance of route = 2605.2

Vehicle: 9

3 − > 31 (21.4) (1) − > 3 (2) − > 30 (21.4) (2) − > 3 (3) − > 28 (21.4) (3) − > 3 (4) − > 28 (14.5) (4) − > 3 (5) − > 40 (21.4) (5) − > 3 (6) − > 32 (21.4) (6) − > 3 (7) − > 32 (21.4) (7) − > 3 (8) − > 40 (21.4) (8) − > 3 (9) − > 56 (21.4) (9) − > 3 (10) − > 28 (18.6) (10) − > 3 (11) − > 27 (20.2) (11) − > 3 (12) − > 32 (21.4) (12) − > 3 (13) − > 27 (21.4) (13) − > 3 (14) − > 31 (21.4) (14) − > 3 (15) − > 71 (21.4) (15) − > 3 (15)

Distance of route = 9797.4

Vehicle: 10

3 − > 71 (21.4) (1) − > 3 (2) − > 31 (15.8) (2) − > 3 (3) − > 40 (21.4) (3) − > 3 (4) − > 31 (21.4) (4) − > 3 (5) − > 71 (11.3) (5) − > 3 (6) − > 56 (21.4) (6) − > 3 (7) − > 27 (12.6) (7) − > 30 (8.8) (7) − > 3 (8) − > 71 (21.4) (8) − > 3 (9) − > 33 (21.4) (9) − > 3 (10) − > 56 (21.4) (10) − > 3 (11) − > 54 (21.4) (11) − > 3 (12) − > 69 (15.8) (12) − > 3 (13) − > 40 (14.1) (13) − > 3 (14) − > 71 (21.4) (14) − > 3 (15) − > 28 (21.4) (15) − > 3 (15)

Distance of route = 8747.9

Vehicle: 11

3 − > 69 (21.4) (1) − > 3 (2) − > 69 (21.4) (2) − > 3 (3) − > 33 (21.4) (3) − > 3 (4) − > 54 (21.4) (4) − > 3 (5) − > 54 (21.4) (5) − > 3 (6) − > 30 (21.4) (6) − > 3 (7) − > 54 (21.4) (7) − > 3 (8) − > 56 (17.26) (8) − > 3 (9) − > 32 (21.4) (9) − > 3 (10) − > 28 (21.4) (10) − > 3 (11) − > 30 (21.4) (11) − > 3 (12) − > 28 (21.4) (12) − > 3 (13) − > 32 (21.4) (13) − > 3 (14) − > 33 (21.4) (14) − > 3 (15) − > 31 (21.4) (15) − > 3 (15)

Distance of route = 9443

Vehicle: 12

3 − > 32 (10.5) (1) − > 3 (1)

Distance of route = 677

Vehicle: 13

4 − > 66 (21.4) (1) − > 4 (2) − > 20 (21.4) (2) − > 4 (3) − > 12 (21.4) (3) − > 4 (4) − > 14 (13.8) (4) − > 12 (7.5) (4) − > 4 (5) − > 7 (21.4) (5) − > 4 (6) − > 7 (21.4) (6) − > 4 (7) − > 25 (21.4) (7) − > 4 (8) − > 25 (21.4) (8) − > 4 (9) − > 20 (21.4) (9) − > 4 (10) − > 15 (21.4) (10) − > 4 (11) − > 66 (21.4) (11) − > 4 (12) − > 12 (21.4) (12) − > 4 (13) − > 25 (21.4) (13) − > 4 (14) − > 20 (13.2) (14) − > 4 (15) − > 15 (21.4) (15) − > 4 (16) − > 15 (21.4) (16) − > 4 (16)

Distance of route = 1135.8

Vehicle: 14

4 − > 25 (21.4) (1) − > 4 (2) − > 22 (9.9) (2) − > 16 (11.4) (2) − > 4 (3) − > 14 (21.4) (3) − > 4 (4) − > 12 (21.4) (4) − > 4 (5) − > 15 (21.4) (5) − > 4 (6) − > 22 (21.4) (6) − > 4 (7) − > 12 (21.4) (7) − > 4 (8) − > 22 (21.4) (8) − > 4 (9) − > 15 (21.4) (9) − > 4 (10) − > 14 (19.4) (10) − > 4 (11) − > 22 (21.4) (11) − > 4 (12) − > 12 (21.4) (12) − > 4 (13) − > 66 (21.4) (13) − > 4 (14) − > 25 (21.4) (14) − > 4 (15) − > 22 (21.4) (15) − > 4 (16) − > 7 (21.4) (16) − > 4 (16)

Distance of route = 1460.4

Vehicle: 15

4 − > 16 (21.4) (1) − > 4 (2) − > 67 (21.4) (2) − > 4 (3) − > 16 (21.4) (3) − > 4 (4) − > 16 (21.4) (4) − > 4 (5) − > 41 (21.4) (5) − > 4 (6) − > 25 (11.7) (6) − > 4 (7) − > 22 (17.7) (7) − > 15 (3.7) (7) − > 4 (8) − > 16 (21.4) (8) − > 4 (9) − > 67 (15.7) (9) − > 4 (10) − > 41 (20.7) (10) − > 4 (11) − > 67 (21.4) (11) − > 4 (12) − > 41 (21.4) (12) − > 4 (13) − > 67 (21.4) (13) − > 4 (14) − > 41 (18.3) (14) − > 7 (3.1) (14) − > 4 (15) − > 41 (21.4) (15) − > 4 (15)

Distance of route = 582.8

Vehicle: 16

4 − > 66 (11.5) (1) − > 4 (2) − > 16 (20.7) (2) − > 4 (2)

Distance of route = 63.0

Vehicle: 17

5 − > 61 (21.4) (1) − > 5 (2) − > 57 (21.4) (2) − > 5 (3) − > 62 (11.0) (3) − > 5 (4) − > 53 (21.4) (4) − > 5 (5) − > 46 (21.4) (5) − > 5 (6) − > 43 (16.7) (6) − > 5 (7) − > 57 (21.4) (7) − > 5 (8) − > 35 (21.4) (8) − > 5 (9) − > 43 (17.89) (9) − > 61 (3.5) (9) − > 5 (10) − > 48 (21.4) (10) − > 5 (11) − > 39 (21.4) (11) − > 5 (12) − > 58 (21.4) (12) − > 5 (12)

Distance of route = 3413.9

Vehicle: 18

5 − > 62 (21.4) (1) − > 5 (2) − > 48 (21.4) (2) − > 5 (3) − > 52 (13.9) (3) − > 48 (7.5) (3) − > 5 (4) − > 48 (21.4) (4) − > 5 (5) − > 46 (21.4) (5) − > 5 (6) − > 62 (21.4) (6) − > 5 (7) − > 46 (21.4) (7) − > 5 (8) − > 58 (13.5) (8) − > 57 (7.9) (8) − > 5 (9) − > 53 (21.4) (9) − > 5 (10) − > 61 (21.4) (10) − > 5 (11) − > 52 (20.6) (11) − > 5 (12) − > 35 (21.4) (12) − > 5 (13) − > 43 (20.1) (13) − > 53 (1.3) (13) − > 5 (13)

Distance of route = 3282

Vehicle: 19

5 − > 52 (19.5) (1) − > 46 (1.9) (1) − > 5 (2) − > 53 (21.4) (2) − > 5 (3) − > 48 (21.4) (3) − > 5 (4) − > 46 (21.4) (4) − > 5 (5) − > 39 (21.4) (5) − > 5 (6) − > 61 (21.4) (6) − > 5 (7) − > 62 (21.4) (7) − > 5 (8) − > 48 (21.4) (8) − > 5 (9) − > 46 (21.4) (9) − > 5 (10) − > 57 (21.4) (10) − > 5 (11) − > 58 (20.1) (11) − > 5 (12) − > 39 (14.39) (12) − > 5 (13) − > 35 (14.7) (13) − > 5 (13)

Distance of route = 3595.8

2st phase (5 clusters variant):

Vehicle: 1

1 − > 9 (21.4) (1) − > 1 (2) − > 35 (21.4) (2) − > 1 (3) − > 50 (21.4) (3) − > 1 (4) − > 35 (21.4) (4) − > 1 (5) − > 50 (21.4) (5) − > 1 (6) − > 43 (21.4) (6) − > 1 (7) − > 6 (21.4) (7) − > 1 (8) − > 33 (21.4) (8) − > 1 (9) − > 50 (21.4) (9) − > 1 (10) − > 46 (21.4) (10) − > 1 (11) − > 6 (21.4) (11) − > 1 (12) − > 35 (21.4) (12) − > 1 (12)

Distance of route = 2072.2

Vehicle: 2

1 − > 46 (16.4) (1) − > 1 (2) − > 35 (15.8) (2) − > 1 (3) − > 36 (21.4) (3) − > 1 (4) − > 35 (21.4) (4) − > 1 (5) − > 43 (20.8) (5) − > 1 (6) − > 36 (21.4) (6) − > 1 (7) − > 9 (21.4) (7) − > 1 (8) − > 33 (19.96) (8) − > 1 (9) − > 9 (21.4) (9) − > 1 (10) − > 35 (18.30) (10) − > 6 (3.1) (10) − > 1 (11) − > 46 (21.4) (11) − > 1 (12) − > 36 (21.4) (12) − > 1 (12)

Distance of route = 2374.8

Vehicle: 3

1 − > 37 (21.4) (1) − > 1 (2) − > 65 (11.45) (2) − > 1 (3) − > 37 (21.4) (3) − > 1 (4) − > 33 (15.3) (4) − > 9 (6.07) (4) − > 1 (5) − > 49 (21.4) (5) − > 1 (6) − > 65 (21.4) (6) − > 1 (7) − > 65 (21.4) (7) − > 1 (8) − > 65 (21.4) (8) − > 1 (9) − > 24 (13.25) (9) − > 36 (8.1) (9) − > 1 (9)

Distance of route = 1013.1

Vehicle: 4

1 − > 24 (19.8) (1) − > 1 (2) − > 64 (21.4) (2) − > 1 (3) − > 37 (21.4) (3) − > 1 (4) − > 49 (21.4) (4) − > 1 (5) − > 24 (21.4) (5) − > 1 (6) − > 48 (21.4) (6) − > 1 (7) − > 37 (17.3) (7) − > 1 (8) − > 49 (21.4) (8) − > 1 (9) − > 64 (11.8) (9) − > 1 (10) − > 6 (21.4) (10) − > 1 (11) − > 48 (21.1) (11) − > 49 (0.3) (11) − > 1 (12) − > 37 (21.4) (12) − > 1 (12)

Distance of route = 1001.9

Vehicle: 5

1 − > 64 (21.4) (1) − > 1 (2) − > 24 (21.4) (2) − > 1 (3) − > 48 (21.4) (3) − > 1 (4) − > 49 (21.4) (4) − > 1 (5) − > 24 (21.4) (5) − > 1 (6) − > 64 (21.4) (6) − > 1 (7) − > 48 (13.6) (7) − > 1 (8) − > 49 (21.4) (8) − > 1 (9) − > 64 (21.4) (9) − > 1 (10) − > 43 (16.4) (10) − > 50 (5.0) (10) − > 1 (11) − > 24 (21.4) (11) − > 1 (11)

Distance of route = 1003.6

Vehicle: 6

2 − > 22 (21.4) (1) − > 2 (2) − > 20 (20.4) (2) − > 2 (3) − > 8 (21.4) (3) − > 2 (4) − > 12 (21.4) (4) − > 2 (5) − > 12 (21.4) (5) − > 2 (6) − > 8 (21.4) (6) − > 2 (7) − > 22 (21.4) (7) − > 2 (8) − > 10 (21.4) (8) − > 2 (9) − > 71 (21.4) (9) − > 2 (9)

Distance of route = 3900

Vehicle: 7

2 − > 8 (21.4) (1) − > 2 (2) − > 10 (20.7) (2) − > 2 (3) − > 28 (21.4) (3) − > 2 (4) − > 12 (21.4) (4) − > 2 (5) − > 17 (21.4) (5) − > 2 (6) − > 28 (21.4) (6) − > 2 (7) − > 71 (21.4) (7) − > 2 (8) − > 28 (21.4) (8) − > 2 (9) − > 22 (21.4) (9) − > 2 (9)

Distance of route = 3759

Vehicle: 8

2 − > 28 (21.4) (1) − > 2 (2) − > 17 (21.4) (2) − > 2 (3) − > 12 (21.4) (3) − > 2 (4) − > 20 (21.4) (4) − > 2 (5) − > 71 (21.4) (5) − > 2 (6) − > 12 (20.0) (6) − > 2 (7) − > 10 (21.4) (7) − > 2 (8) − > 28 (21.4) (8) − > 2 (9) − > 10 (21.4) (9) − > 2 (9)

Distance of route = 3620

Vehicle: 9

2 − > 58 (21.4) (1) − > 2 (2) − > 67 (21.4) (2) − > 2 (3) − > 67 (21.4) (3) − > 2 (4) − > 17 (20.1) (4) − > 58 (1.3) (4) − > 2 (5) − > 10 (18.49) (5) − > 8 (2.91) (5) − > 2 (5)

Distance of route = 825.5

Vehicle: 10

2 − > 17 (21.4) (1) − > 2 (2) − > 67 (11.54) (2) − > 2 (3) − > 12 (12.8) (3) − > 28 (8.5) (3) − > 2 (4) − > 58 (21.4) (4) − > 2 (5) − > 17 (19.1) (5) − > 2 (6) − > 20 (17.02) (6) − > 22 (4.4) (6) − > 2 (7) − > 71 (11.54) (7) − > 2 (8) − > 67 (21.4) (8) − > 2 (9) − > 58 (21.4) (9) − > 2 (9)

Distance of route = 2114.9

Vehicle: 11

3 − > 39 (21.4) (1) − > 3 (2) − > 30 (21.4) (2) − > 3 (3) − > 30 (21.4) (3) − > 3 (4) − > 30 (21.4) (4) − > 3 (5) − > 32 (21.4) (5) − > 3 (6) − > 68 (21.4) (6) − > 3 (7) − > 26 (20.1) (7) − > 3 (8) − > 69 (21.4) (8) − > 3 (9) − > 30 (21.4) (9) − > 3 (10) − > 70 (21.4) (10) − > 3 (11) − > 27 (21.4) (11) − > 3 (12) − > 69 (21.4) (12) − > 3 (12)

Distance of route = 8537

Vehicle: 12

3 − > 25 (21.4) (1) − > 3 (2) − > 32 (21.4) (2) − > 3 (3) − > 70 (21.4) (3) − > 3 (4) − > 26 (21.4) (4) − > 3 (5) − > 29 (21.4) (5) − > 3 (6) − > 25 (21.4) (6) − > 3 (7) − > 29 (21.4) (7) − > 3 (8) − > 70 (21.4) (8) − > 3 (9) − > 25 (18.14) (9) − > 3 (10) − > 69 (21.4) (10) − > 3 (11) − > 27 (21.4) (11) − > 3 (12) − > 29 (21.4) (12) − > 3 (12)

Distance of route = 8878

Vehicle: 13

3 − > 68 (21.4) (1) − > 3 (2) − > 31 (21.4) (2) − > 3 (3) − > 25 (21.4) (3) − > 3 (4) − > 39 (21.4) (4) − > 3 (5) − > 25 (21.4) (5) − > 3 (6) − > 31 (21.4) (6) − > 3 (7) − > 32 (21.4) (7) − > 3 (8) − > 27 (21.4) (8) − > 3 (9) − > 68 (15.7) (9) − > 3 (10) − > 27 (21.4) (10) − > 3 (11) − > 39 (21.4) (11) − > 3 (12) − > 70 (21.4) (12) − > 3 (12)

Distance of route = 9002

Vehicle: 14

3 − > 39 (14.1) (1) − > 3 (2) − > 53 (21.4) (2) − > 3 (3) − > 31 (21.4) (3) − > 3 (4) − > 31 (21.4) (4) − > 3 (5) − > 30 (15.8) (5) − > 3 (6) − > 31 (17.4) (6) − > 3 (7) − > 27 (15.3) (7) − > 69 (6.1) (7) − > 3 (8) − > 25 (10.1) (8) − > 70 (11.3) (8) − > 3 (9) − > 54 (21.4) (9) − > 3 (10) − > 55 (20.7) (10) − > 3 (10)

Distance of route = 5869.2

Vehicle: 15

3 − > 54 (21.4) (1) − > 3 (2) − > 27 (17.9) (2) − > 3 (3) − > 53 (21.4) (3) − > 3 (4) − > 55 (17.9) (4) − > 54 (3.4) (4) − > 3 (5) − > 31 (14.5) (5) − > 32 (6.9) (5) − > 3 (6) − > 55 (21.4) (6) − > 3 (7) − > 53 (21.4) (7) − > 3 (8) − > 53 (21.4) (8) − > 3 (9) − > 55 (21.4) (9) − > 3 (10) − > 26 (12.6) (10) − > 29 (8.8) (10) − > 3 (11) − > 54 (21.4) (11) − > 3 (11)

Distance of route = 4641.3

Vehicle: 16

4 − > 59 (21.4) (1) − > 4 (2) − > 45 (21.4) (2) − > 4 (3) − > 56 (21.4) (3) − > 4 (4) − > 57 (21.4) (4) − > 4 (5) − > 47 (21.4) (5) − > 4 (6) − > 52 (21.4) (6) − > 4 (7) − > 45 (21.4) (7) − > 4 (8) − > 47 (21.4) (8) − > 4 (9) − > 62 (19.9) (9) − > 4 (10) − > 34 (19.5) (10) − > 45 (1.8) (10) − > 4 (10)

Distance of route = 2833.8

Vehicle: 17

4 − > 38 (17.9) (1) − > 4 (2) − > 34 (16.6) (2) − > 4 (3) − > 63 (21.4) (3) − > 4 (4) − > 62 (21.4) (4) − > 4 (5) − > 38 (17.89) (5) − > 60 (3.5) (5) − > 4 (6) − > 42 (13.5) (6) − > 56 (7.9) (6) − > 4 (7) − > 63 (21.4) (7) − > 4 (8) − > 38 (21.4) (8) − > 4 (9) − > 60 (21.4) (9) − > 4 (10) − > 52 (21.4) (10) − > 4 (10)

Distance of route = 3830.8

Vehicle: 18

4 − > 47 (21.4) (1) − > 4 (2) − > 59 (13.9) (2) − > 47 (7.5) (2) − > 4 (3) − > 56

(21.4) (3) − > 4 (4) − > 51 (21.4) (4) − > 4 (5) − > 45 (21.4) (5) − > 4 (6) − > 47 (21.4) (6) − > 4 (7) − > 63 (21.4) (7) − > 4 (8) − > 56 (21.4) (8) − > 4 (9) − > 42 (21.1) (9) − > 4 (10) − > 59 (21.4) (10) − > 4 (10)

Distance of route = 2932.9

Vehicle: 19

4 − > 51 (21.4) (1) − > 4 (2) − > 47 (21.4) (2) − > 4 (3) − > 59 (20.6) (3) − > 4 (4) − > 52 (21.4) (4) − > 4 (5) − > 34 (21.4) (5) − > 4 (6) − > 45 (21.4) (6) − > 4 (7) − > 45 (21.4) (7) − > 4 (8) − > 60 (21.4) (8) − > 4 (9) − > 60 (21.4) (9) − > 4 (10) − > 57 (21.4) (10) − > 4 (10)

Distance of route = 2688

Vehicle: 20

4 − > 57 (13.1) (1) − > 4 (2) − > 42 (20.08) (2) − > 52 (1.3) (2) − > 4 (3) − > 61 (11.0) (3) − > 4 (4) − > 59 (10.1) (4) − > 51 (11.2) (4) − > 4 (5) − > 61 (21.4) (5) − > 4 (6) − > 61 (21.4) (6) − > 4 (7) − > 62 (16.4) (7) − > 63 (4.9) (7) − > 4 (8) − > 61 (21.4) (8) − > 4 (8)

Distance of route = 2009.7

Vehicle: 21

5 − > 15 (21.4) (1) − > 5 (2) − > 41 (21.4) (2) − > 5 (3) − > 41 (21.4) (3) − > 5 (4) − > 40 (21.4) (4) − > 5 (5) − > 21 (21.4) (5) − > 5 (6) − > 13 (21.4) (6) − > 5 (7) − > 23 (21.4) (7) − > 5 (8) − > 14 (21.4) (8) − > 5 (9) − > 66 (21.4) (9) − > 5 (10) − > 19 (20.8) (10) − > 5 (11) − > 23 (21.4) (11) − > 5 (12) − > 40 (21.4) (12) − > 5 (13) − > 19 (21.4) (13) − > 5 (14) − > 23 (21.4) (14) − > 5 (15) − > 15 (20.4) (15) − > 5 (15)

Distance of route = 3473.1

Vehicle: 22

5 − > 15 (21.4) (1) − > 5 (2) − > 11 (21.4) (2) − > 5 (3) − > 21 (21.4) (3) − > 5 (4) − > 14 (21.4) (4) − > 5 (5) − > 15 (21.4) (5) − > 5 (6) − > 18 (21.4) (6) − > 5 (7)

− > 11 (21.4) (7) − > 5 (8) − > 7 (21.4) (8) − > 5 (9) − > 41 (21.4) (9) − > 5 (10) − > 40 (21.4) (10) − > 5 (11) − > 23 (21.4) (11) − > 5 (12) − > 14 (21.4) (12) − > 5 (13) − > 44 (21.4) (13) − > 5 (14) − > 18 (21.4) (14) − > 5 (15) − > 44 (21.4) (15) − > 5 (15)

Distance of route = 3058.4

Vehicle: 23

5 − > 23 (13.8) (1) − > 5 (2) − > 14 (21.4) (2) − > 5 (3) − > 7 (21.4) (3) − > 5 (4) − > 44 (21.4) (4) − > 5 (5) − > 66 (21.4) (5) − > 5 (6) − > 11 (21.4) (6) − > 5 (7) − > 11 (21.4) (7) − > 5 (8) − > 14 (21.4) (8) − > 5 (9) − > 21 (21.1) (9) − > 5 (10) − > 11 (21.4) (10) − > 5 (11) − > 18 (21.4) (11) − > 5 (12) − > 21 (21.4) (12) − > 5 (13) − > 66 (21.4) (13) − > 5 (14) − > 13 (21.4) (14) − > 5 (15) − > 40 (21.4) (15) − > 5 (15)

Distance of route = 3093.5

Vehicle: 24

5 − > 16 (21.4) (1) − > 5 (2) − > 40 (17.6) (2) − > 5 (3) − > 16 (21.4) (3) − > 5 (4) − > 16 (11.89) (4) − > 5 (5) − > 15 (16.0) (5) − > 18 (5.4) (5) − > 5 (6) − > 21 (17.8) (6) − > 14 (3.7) (6) − > 5 (7) − > 16 (21.4) (7) − > 5 (8) − > 21 (10.3) (8) − > 44 (11.1) (8) − > 5 (9) − > 66 (15.7) (9) − > 5 (10) − > 15 (17.1) (10) − > 41 (4.3) (10) − > 5 (11) − > 7 (12.0) (11) − > 5 (12) − > 19 (13.8) (12) − > 11 (7.5) (12) − > 5 (13) − > 13 (11.8) (13) − > 5 (13)

Distance of route = 2646.7